SCHEDULE SPACES: AN EMPIRICAL AND CONCEPTUAL ANALYSIS

BY

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS ii

LIST OF FIGURES v

ABSTRACT xii

CHAPTERS

1 INTRODUCTION 1

Controlling Variables, Independent Variables and "Traditional" Approaches to Schedules of Reinforcement 1

The Fundamental Schedule-Space Approach 9

The t-t System 17

Interlocking Schedules 23

The Interactive Schedule 24

Rachlin's Approach 27

A Comparison of the Systems 28

Purpose of Experiments 61

2 METHOD 65

Subjects 65

Apparatus 65

Procedure 66

3 RESULTS 77

Stable States 77

Transitions 148

Changes in the Character of Transitions 233

4 DISCUSSION 245

Overall Response Rates: Stable States 245

Overall Response Rates: Transitions 266

Molecular Data: Stable States 269

Molecular Data: Transitions 280

The Future of Schedule-Space Research 282

Molecularism, Molarism, Controlling Variables, and the Independent Variable Approach 289

Combinations of Molecular and Molar Explanations 294

Molecular Interpretations of the Results 294

Molar Interpretations of the Results 300

The Falsifiability of Molar and Molecular Positions 303

5 CONCLUSIONS 309

REFERENCES 315

BIOGRAPHICAL SKETCH 321

LIST OF FIGURES

Figure 1. Experimental domain of the schedule space 13

Figure 2. Some feedback functions from within the experimental domain 16

Figure 3. Some feedback functions from the T- and interactive schedule systems 20

Figure 4. Response rate as a function of RTE and BI for rats in Berryman & Nevin (1962) 34

Figure 5. Response rate as a function of RTE and BI for rats in Powers (1958) 38

Figure 6. Response rate as a function of RTE and BI for rats in Rider (1977) 42

Figure 7. Response rate as a function of RTE and BI for rats in Ettinger et al. (1987) 45

Figure 8. Response rate as a function of RTE and BI for rats in Ettinger et al (1987) under 'linear VI with ratio subtraction' schedules 53

Figure 9. Response rate as a function of RTE and BI for rats in Vaughn and Miller (1984) under 'linear VI with ratio subtraction' schedules 55

Figure 10. Feedback functions for FR 36 and two interlocking schedules which have FR 36 as their ratio base 60

Figure 11. Feedback functions for VI 60 s and for a 'matched' ratio schedule 69

Figure 12. Response rate during, from left to right, the last 10 sessions under, VI 60 s, the first and last 10 sessions under experimental phases and the first 10 sessions following the return to VI 60 s 79

Figure 13. Percent VI maximum response rate as a function of the percent VR under baseline and experimental conditions 82

Figure 14. Maximum response rate under baseline and experimental phases as a function of BI and RTE 85

Figure 15. Rate of response as a function of sessions under some experimental phases for all three pigeons . . 88

Figure 16. Distribution of all IRTs, distribution of reinforced IRTs and IRT/OP functions for the last session under each of 3 baseline phases for Pigeon 1097 91

Figure 17. Distribution of all IRTs, distribution of reinforced IRTs and IRT/OP functions for the last session under each of 3 baseline phases for Pigeon 5994 93

Figure 18. Distribution of all IRTs, distribution of reinforced IRTs and IRT/OP functions for the last session under each of 3 baseline phases for Pigeon 2760 95

Figure 19. Distribution of all IRTs, distribution of reinforced IRTs and IRT/OP functions for the last session under each of 3 experimental phases for Pigeon 1097 97

Figure 20. Distribution of all IRTs, distribution of reinforced IRTs and IRT/OP functions for the last session under each of 3 experimental phases for Pigeon 5994 99

Figure 21. Distribution of all IRTs, distribution of reinforced IRTs and IRT/OP functions for the last session under each of 3 experimental phases for Pigeon 2760 101

Figure 22. Average IRT duration as a function of ordinal position post-reinforcement during the last 3 sessions under a representative experimental condition and its preceding baseline phase for Pigeon 1097 107

Figure 23. Average IRT duration as a function of ordinal position post-reinforcement during the last 3 sessions under a representative experimental condition and its preceding baseline phase for Pigeon 5994 109

Figure 24. Average IRT duration as a function of ordinal position post-reinforcement during the last 3 sessions under a representative baseline phase for Pigeon 2760 111

Figure 25. IRT durstlon ss s function of ordinsl position post-reinforcement for some sslected interreinforcement intervals which occurred during the lsst sssslon under s represeststive experimentsl condition and its preceding bssslins phsss for Pigeon 1097 114

Figure 26. IRT duration as s function sf srdinal position post-reinforcement for some sslected isterreinforcement intervals which occurred during the lsst session under s representstive experimentsl condition and lts preceding bsssline phsss for Pigeon 5994 116

Figure 27. IRT durstion ss s function of ordinsl position post-reinforcement for some sslected interreinforcement intervals which occurred during ths lsst sssslon under s representative bsssline phsse for Pigeon 2760 118

Figure 28. IRT durstion ss s function of ordinal position in ths sssslon during ths lsst 3 sssslons under s represeststive experimentsl condition and lts preceding bsssslins phsss for Pigesn 1097 121

Figure 29. IRT durstion ss s function of ordinal position ln ths session during the lsst 3 sssslons under s represantstlve sxperimental condition snd lts preceding bsssline phsss for Pigeon 5994 123

Figure 30. IRT durstion ss s function of ordinal positlon in the sssslon during ths lsst 3 sessions under s representstive bsssline phsss for Plgson 2760 125

Figure 31. Oversll sesslon response rstes during ths first and lsst 10 sssslons of most phsss in Experiment 2 129

Figure 32. Maximum responss rste ss s function of BI and RTE under esch type of schsduls in Experiment 2 132

Figure 33. IRT distributions, IRTS/OP, and the distribution of dslays to relnforcement for the lsst session of VT 600 s, RTE=-15 0 s for sll three pigeons in Experiment 2 135

Figure 34. IRT distributions, IRTS/OP, and ths distribution of dmlays to rsinforcement for ths lsst sesslon of VT t s for Pigeons 1694 and 1404 . 137

Figure 35. Average IRT durstion ss s function of ordinsl position post-rsinforcement during the lsst 3 sssslons under VT 600 s, RTE=-15 0 s for sll three pigeons in Experimsnt 2 142

Figure 36. Cumulative number of responses and reinforcers as a function of time in session for Pigeons 1654 and 1404 during the last three sessions under VT t s 144

Figure 37. IRT duration as a function of ordinal position post-reinforcement during selected interreinforcement intervals under VT 600 s, RTE=-15.0 s for all three pigeons in Experiment 2 . . . 147

Figure 38. IRT duration as a function of ordinal position in the session during the last 3 sessions under VT 600 s, RTE=-15.0 s for all three pigeons in Experiment 2 150

Figure 39. Overall response rate as a function of sessions following the change from baseline to experimental phase during two different transitions for Pigeons 1097 (top panel) and 5994 153

Figure 40. Relative frequency of different IRTS for the first 9 sessions following the change from baseline to a representative experimental phase (VI 3000 s, RTE=-49.0 s) for Pigeon 1097 155

Figure 41. Relative frequency of different IRTS for selected sessions following the change from baseline to a representative experimental phase (VI 600 s, RTE=-8.5 s) for Pigeon 5994 160

Figure 42. Relative frequency of different IRTS for selected sessions following the change from baseline to a representative experimental phase (VI 600 s, RTE=-12.2 s) for Pigeon 2760 162

Figure 43. IRT duration as a function of ordinal position in the session for selected sessions during the transition from baseline to a representative experimental phase (VI 3000 s, RTE=-49.0 s) for Pigeon 1097 165

Figure 44. IRT duration as a function of ordinal position in the session for selected sessions during the transition from baseline to a representative experimental phase (VI 600 s, RTE=-8.5 s) for Pigeon 5994 167

Figure 45. Overall response rate as a function of sessions following the return to baseline from an experimental phase for all 3 pigeons in Experiment 1 . 171

Figure 46. Overall response rate as a function of sessions following the return to baseline from VI 240 s, RTE=-2.4 s for Pigeon 1097 173

Figure 47. IRT duration as a function of ordinal position in the session for three consecutive sessions during the transition back to baseline for all three Pigeons in Experiment 1 176

Figure 48. IRT duration as a function of ordinal position in the session for some selected sessions during the transition depicted in Figure 43 for Pigeon 1097 179

Figure 49. Overall response rate as a function of sessions following the change from VT 300 s, RTE=t s to VT t s for all three pigeons in Experiment 2 . . . 183

Figure 50. Relative frequency of different IRTS for selected sessions during the transition to VT for Pigeon 1694 186

Figure 51. Relative frequency of different IRTS for selected sessions during the transition to VT for Pigeon 1404 188

Figure 52. Relative frequency of different IRTS for selected sessions during the transition to VT for Pigeon 3673 190

Figure 53. IRT duration as a function of ordinal position in the session for selected sessions during the transition to VT for Pigeon 1694 194

Figure 54. IRT duration as a function of ordinal position in the session for selected sessions during the transition to VT for Pigeon 1404 196

Figure 55. IRT duration as a function of ordinal position in the session for selected sessions during the transition to VT for Pigeon 3673 198

Figure 56. Overall response rate as a function of sessions following the change from VT to the phase in which responses added time to the currently scheduled interval for Pigeons 1694 and 1404 201

Figure 57. Relative frequency of different IRTS for selected sessions during the transition to the phase in which responses added time to the currently scheduled interval for Pigeon 1694 204

Figure 58. Relative frequency of different IRTS for the first session during the transition to the phase in which responses added time to the currently scheduled interval for Pigeon 1404 206

Figure 59. IRT duration as a function of ordinal position in the session for selected sessions during the transition to the phase in which responses added time to the currently scheduled interval for Pigeon 1694 208

Figure 60. IRT duration as a function of ordinal position in the session for the first session during the transition to the phase in which responses added time to the currently scheduled interval for Pigeon 1404 210

Figure 61. Overall response rate as a function of sessions following the return to VT for Pigeons 1694 and 1404 213

Figure 62. Relative frequency of different IRTS for selected sessions during the return to VT for Pigeon 1694 215

Figure 63. Relative frequency of different IRTS for selected sessions during the return to VT for Pigeon 1404 217

Figure 64. IRT duration as a function of ordinal position in the session for selected sessions during the return to VT for Pigeon 1694 . . . 220

Figure 65. IRT duration as a function of ordinal position in the session for selected sessions during the return to VT for Pigeon 1404 222

Figure 66. Overall response rate as a function of sessions following the return to VT 300 s, RTE=-t s for all three pigeons in Experiment 2 225

Figure 67. Relative frequency of different IRTS for selected sessions during the return to VT 300 s, RTE=-t s for Pigeon 1694 227

Figure 68. Relative frequency of different IRTS for the first four sessions during the return to VT 300 s, RTE=-t s for Pigeon 1404 229

Figure 69. Relative frequency of different IRTS for the third through eighth sessions during the return to VT 300 s, RTE=-t s for Pigeon 3673 . . . 231

Figure 70. IRT duration as a function of ordinal position in the session for selected sessions during the return to VT 300 s, RTE=-t s for Pigeon 1694 . . 234

Figure 71. IRT duration as a function of ordinal position in the session for the first four sessions during the return to VT 300 s, RTE=-t s for Pigeon 1404 236

Figure 72. IRT duration as a function of ordinal position in the session for the third through eighth session during the return to VT 300 s, RTE=-t s for Pigeon 3673 238

Figure 73. Overall response rate as a function of sessions during transitions from baselins "early" and "late" in Experiment 1 for Pigeons 1097 and 5994 . . . 241

Figure 74. Relative frequency of different IRTS from the last session of baseline preceding the "early" transitions depicted in Figure 73 for Pigeons 1097 and 5994 244

Figure 75. Hypothetical curves representing responses rate or maximum response rate as a function of RTE and RI 251

Figure 76. Hypothetical curves showing discontinuous stable-states in a cross-section of the surface formed when response rate is plotted as a function of RTE and RI 256

Figure 77. Responses per session as a function of the estimates of RI and RTE from 1 group of subjects in Berger's (1969) experiment 260

Figure 78. Feedback functions for some symmetrical schedules of positive and negative reinforcement . . . 281

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SCHEDULE SPACES: AN EMPIRICAL AND CONCEPTUAL ANALYSIS

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Parametric manipulation of a "traditional" reinforcement schedule yields "phenomenological" laws relevant only to the particular type of schedule investigated. Many different types of schedules may be viewed as loci within schedule spaces defined by multiple parameters. Manipulation of these parameters should yield laws which encompass many kinds of schedules. These laws can be viewed as facts to be explained by the "controlling variable" approach, which implies that schedule-controlled behavior can be understood in terms of something like a system of coupled, differential equations.

In the three-parameter schedule space considered here, an event is scheduled to occur according to the *base interevent* interval (BI). Considered in isolation, the BI is simply a time-schedule. Responses may, however, subtract time from, or add time to, the current interval arranged by the BI (*response-time exchange value*; RTE). A third parameter, a,

determines the amount of time which must pass--after the event would otherwise be scheduled on the basis of the former two parameters--for the event actually to occur, *given no response*. If a response occurs during this latter temporal interval, the event occurs immediately. *DI* and *RTS* arrange a continuum of dependency between responses and events, while *a* and *DI* arrange a continuum encompassing response-independent events and events which must occur temporally contiguous with responses. When all three parameters are considered, the resulting space encompasses, time, interval, ratio, interlocking time-ratio, interlocking interval-ratio, and event-postponement schedules. It also includes schedules similar to differential reinforcement of low rate schedules, as well as continuously present "events" and extinction. In the experiments reported here, pigeons were exposed to schedules from within 2 cross-sections of the space--where *a*=0 (no necessary temporal contiguity) or infinity (events must be temporally contiguous with responses).

The goal of the experiments was simply to provide a detailed analysis of responding controlled by schedules from within these spaces. Stable-states and transitions were analyzed in terms of session response rates and sequences and distributions of interresponse times.

CHAPTER 1

INTRODUCTION

Controlling-Variables, Independent Variables and "Traditional" Approaches to Schedules of Reinforcement

In the terminology established by Skinner (1938), the most commonly used schedules of reinforcement may be placed in one of four cells in a 2 x 2 matrix with headings fixed vs. variable and ratio vs. interval. In ratio schedules the occurrence of a consequence depends on the emission of responses only, while in interval schedules the consequence is dependent on a response only after the passage of some amount of time. In "fixed" schedules, the criterion for reinforcement remains the same from reinforcer to reinforcer, whereas in "variable" schedules it does not. Although there are distinct rates and patterns of responding maintained by these schedules, the terminology reflects differences in terms of what the experimenter does; that is, it reflects differences in schedules as independent variables. (The term independent variable will be used to refer only to variables that exist *independent* of responding. A particular schedule can be programmed independent of behavior and is, thus, by this definition an independent variable.) This is certainly a reasonable basis for the systematization of a field. There does, however,

seem to be a drawback, and despite the fact that the terminology is still widely accepted there is a sense in which the straightforward systematization it suggests is not. The problem with a systematization in terms of categorical independent variables is that the dimensions along which the distinctions are made are incommensurate with respect to each other. Relating a dependent variable to schedule parameter as the independent variable gives us an "empirical law" that is valid only with respect to a particular schedule type. If we manipulate the type of schedule, the differences in the independent variables can only be described qualitatively. Empirical laws that 'cut across' schedule types seem impossible if the systematization is based solely on categorical independent variables.

Skinner's view of schedules changed over the years, but the position that he had adopted by the 1950s suggested a way out of the dilemma. In *Science and Human Behavior* (Skinner, 1953; p 85) he wrote that schedules are "simply rather inaccurate ways of reinforcing rates of responding" and in *Schedules of Reinforcement* (Ferster & Skinner, 1957) that

> Under a given schedule of reinforcement, it can be shown that at the moment of reinforcement a given set of stimuli will usually prevail. A schedule is simply a convenient way of arranging this. Reinforcement occurs in the presence of such stimuli, and the future

> behavior of the organism is in part controlled by them or by similar stimuli according to a well established principle of operant discrimination (p. 3).

Thus, all schedules of reinforcement were said to share common *kinds* of variables and a systematization in terms of them should cut across schedule type. Although Skinner's discussion is consistent with "molecularism"--the view that the effects of schedules can be understood in terms of differentiation of response classes and/or discrimination based on events in close temporal proximity to reinforcement--statements he makes later show that he accepted the possibility that rate of reinforcement was an operative variable, i.e., a "molar" view (Ferster & Skinner, 1957, p. 400). Skinner's position seems, thus, to have been the basis of three movements; molecularism, molarism and an approach to which they are subordinate. This last, superordinate, approach will be referred to as the *controlling-variable approach*, after Zeller (1977).

Following Skinner's lead, Zeller (1977) outlined what he believed had been the overall strategy of reinforcement-schedule research. Schedules, he argued, are composed of *direct* and *indirect* variables. Direct variables are those that exist solely because of the experimenter's arrangements. Examples are maximum rate of reinforcement under interval schedules and number of responses per reinforcer under ratio schedules. Notice that direct variables are, in fact, what would usually be called

independent variables. Indirect variables, on the other hand, are variables that are not given solely by the arrangement but depend, rather, on the behavior of the organism. Rate of reinforcement under a ratio schedule is an example of an indirect variable. These are variables that are said to "control" behavior but they are not independent of behavior. Describing this approach, Zeiler (1984, p. 489) writes: "Instead of being treated as irreducible causes of behavior, schedules are considered as complex independent variables that bring into play a set of more basic controlling conditions." Notice that Zeiler's usage of the term "independent variable" is somewhat confusing; it is possible for schedules to be "complex independent variables" but schedules are not *composed* of independent variables according to the controlling-variable approach; variables that are indirect under a particular schedule simply cannot be independent variables with respect to those same schedules. The controlling-variable approach is not, however, silent on the issue of independent variables; one way to investigate the effects of indirect variables is to arrange conditions under which they are direct (independent) variables. With the variable under the experimenter's control, the establishment of the function relating behavior to the variable is a straightforward empirical matter. This last step would seem to move the

controlling-variable approach into line with a schedules-as-irreducible-independent-variables approach.

In recent years the controlling-variable approach has been criticized (Marr, 1982; Zeiler, 1984) on grounds immediately relevant to the current discussion. Referring to Zeiler's (1977) paper, Marr (p. 206) writes, "Zeiler suggests that to evaluate the role of indirect variables in determining schedule performance, one should impose that variable directly. Changing an indirect variable to a direct one will likely change performance, but it will not necessarily tell us how, or even if, that variable exerts its effects indirectly." Zeiler (1984, p. 430) raises a similar issue; he writes, "One also wonders if the effort must not lead inevitably to infinite regression, given that each presumed variable can itself only be studied in the context of a schedule that presumably would have to be analyzed itself!" Both of these statements point to the fact that the original problem--to determine the role of variables that are relevant across different types of schedules--has not really been solved. Indeed, the problem cannot be solved in a strictly empirical fashion where the operative variables are not independent variables.

Consider a system of differential equations such as that below.

1.) $dX1/dt=f(X1, X2, X3, X4)$,

2.) $dX2/dt=f(X1)$,

3.) dX3/dt=f(X1), and

4.) dX4/dt=f(X1)

This system represents, in the abstract, what is asserted to be true of behavior as a system. The "effects" of particular variables depend on the level of other variables. Let us say, for the sake of argument, that X1 is rate of responses, X2 is rate of reinforcement, X3 is the number of responses per reinforcer and X4 is mean reinforced interresponse time. Notice that equations 2 through 4 depend on the experimenter's arrangement. Equation 2, for example, must be a constant under a ratio schedule, but must be some monotonic, negatively accelerated, decreasing function for interval schedules. When variables X2 through X4 are made direct (independent) variables by changing the schedule, the form of equations 2-4 change. Each schedule, then, would have its own unique configuration of equations. What we want to know is Equation 1 because it is the expression describing how these variables interact, but, from a strictly empirical standpoint, all that can be known is the values taken by X1 through time under unique sets of conditions. The main point here, however, is not that the controlling-variable approach is "wrong" or that the research conducted in the experimental analysis of behavior is flawed. The main point is that the approach cannot yield a quantitative systematization through directly empirical means.

It may be argued that to depict behavioral systems with differential equations, even in such a general, hypothetical fashion, is inappropriate since this is rarely an approach taken by behavioral analysts. The argument is not, however, affected by considering quantitative approaches which have as their goal the specification of steady-states in terms of controlling-variables. Differential equations are presented here because this is the kind of complicated system which is *implied*--and rightly so--by the controlling-variable approach. Actually to find an equation like Equation 1 that had as its argument variables covering a wide range of schedules would be an advance in the quantitative treatment of schedule-controlled behavior of substantial import. An elucidation of such a system should be one of the ultimate goals of the controlling-variable approach.

It might be argued that it is erroneous to pit the controlling-variable approach against the schedules-as-irreducible-variables approach. Ferster and Skinner (1957), for example, argued that the controlling-variable approach (though they did not call it that) entailed an *explanation* of the functions obtained by the straightforward empirical investigation of schedules. This position is not, however, at odds with the position being expressed here. The two approaches are complementary, but there is one essential difference: a systematization strictly in terms of independent variables leads immediately to empirical laws. Laws at the level of controlling variables must ultimately

rely on the hypothetico-deductive method; the form of Equation 1 must be guessed, within-subject constants must be empirically determined, and quantitative predictions of the effects of other schedules must be made on this basis. The approaches are complementary because the straightforward manipulation of independent variables yield the phenomena that are to be explained.

While the independent-variable approach produces sparse laws, these laws may be much more encompassing than is currently realized. It is possible, for example, to produce a 3-dimensional continuum of schedules within which are located interval, ratio, and time schedules (Zeiler, 1977; a time schedule is one in which events occur independent of behavior), as well as schedules of negative reinforcement and some other schedules that never have been investigated. This means that there must be one equation in three variables that completely describes the steady-states produced by many "simple" positive reinforcement schedules as well as all those to which these traditional schedules are continuously related, including negative reinforcement schedules. The remainder of the first chapter will be concerned with elucidating such a scheme, comparing it, conceptually, to similar approaches, and, finally, a discussion of the data generated by the alternative approaches.

The Fundamental Schedule-Space Approach

There are several directions in which the basic idea presented here may evolve and a few possibilities will be discussed. The essential features of the system, however, remain the same across all these possibilities.

The core of the system is two temporal intervals; the base *interresponse interval* (BI) and the *response/time exchange* value (RTE). The occurrence of events is arranged according to the BI (which may or may not vary from event to event) but responses may add or subtract time from the currently scheduled interval. The amount of time added or subtracted is the RTE value. With just these two parameters it is possible to arrange previously undefined schedules of negative reinforcement, previously undefined schedules similar to differential-reinforcement-of-other-behavior (DRO) schedules (Reynolds, 1961; see below), time schedules (Zeller, 1977), interlocking (Ferster & Skinner, 1957) time-ratio schedules, and ratio schedules. (An interlocking schedule is one in which progress in one component affects the criteria for reinforcement in another, essentially concurrent, component. Despite this general definition, interlocking schedules are typically understood to be schedules in which a ratio-schedule value changes as a function of the passage of time. A DRO schedule is one in which an event occurs at the end of a specified time period given that a particular response does not occur. Occurrence of this response resets the timer.) When RTE is positive

(responses *add* time) there is a negative correlation between rate of responding and rate of the consequence. When RTE=0 there is no correlation, and when RTE is negative there is a positive correlation between responding and the consequence. When RI-->∞ and RTE gets commensurately large, ratio schedules, or schedules very near to ratio schedules, are arranged. (In order for "true" ratio schedules to be arranged with just these two dimensions, RTE must be large and all of the intervals in the RI list must be integral multiples of RTE. If this were not so responses might subtract off enough time so that an event would be scheduled to occur in, for example, 1 s. If a response did not occur before this time elapsed the event would occur and it would not be contiguous with a response and, thus, the schedule could not be a true ratio schedule.)

When a third parameter, s, is added, interval schedules and interlocking interval-ratio schedules are definable within the space as well as some schedules that closely resemble differential reinforcement of low rate (DRL) schedules (Ferster & Skinner, 1957), also referred to as IRT>t schedules (Zeller, 1977). This parameter also has the dimension of time--it is the maximum time until an event occurs after the RI value has counted down to zero, *given no responses*. If a response occurs, the event follows immediately. The schedules arranged in this space are, thus, tandem schedules (Ferster & Skinner, 1957), though this may be true in principle only when the parameter goes

to zero or infinity. A tandem schedule is one in which reinforcement occurs after the completion of two or more schedules which operate in sequence but in the presence of the same stimulus conditions. The s parameter may assume any value between 0 and infinity, inclusive. Figure 1 shows a diagram of these three dimensions, RTE, BI, and s. The x-, y-, and z-axes are RTE, s, and BI, respectively. The space is divided at RTE=0 by the vertical interval-time plane. Time schedules exist where s=0 and interval schedules exist where s-->infinity. Except for schedules which lie on the x-axis, all schedules to the left of the interval-time plane arrange a positive correlation between responding and consequence. Points along the x-axis are not, properly speaking, schedules at all; here, the "consequent event" is continuously present for the entire session. The front panel to the left of the interval-time plane is a continuum between continuously present "events" and fixed-ratio (FR) 1 schedules. Ratio schedules lie in the back plane. Interlocking interval-ratio and time-ratio schedules are located on the top and bottom planes on the left. All of the schedules which are not at the limits are in the continuum between interlocking interval-ratio and time-ratio schedules. On the right side of the figure (RTE>0) are schedules in which there is a negative correlation between rate of responding and rate of reinforcement. As s is increased from zero the feedback functions (See below) become bitonic; increases in response

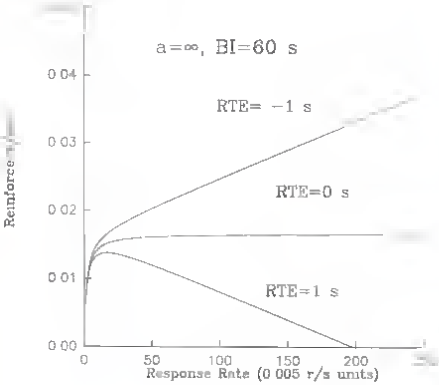
Figure 1 Experimental domain of the schedule space. X-axis: response-time exchange value (RTE); Y-axis: "A" parameter; Z-axis: Bass interval value (BI)

a
∞
0
— ∞
0
∞
RTE
0
B_1
VI
VI

rates, when rates of response are very low, result in increases in the rate of reinforcement. At higher rates of response further increases result in decreases in rate of reinforcement. The back panel on the right side contains traditional extinction.

One way to describe a contingency is to display its feedback function (Hsum, 1973, 1983) which depicts rate of reinforcement as a function of rate of responding. In doing so the superiority of the molar perspective is not implied; feedback functions are here treated, unless otherwise noted, as quantitative descriptions of contingencies. There is, however, a drawback to using feedback functions as descriptions; a feedback function does not uniquely identify a particular kind of schedule. Interlocking FR fixed-interval (FI) schedules would have, for example, the same molar feedback function as mixed or tandem FR FI. A mixed schedule is one in which two or more schedules alternate in the presence of the same stimulus conditions (Skinner, 1957). Figure 2 shows some feedback functions for the portion of the space where s-->∞ BI is held constant at 60 s and RTE is either 1.0, -1.0 or zero s. When RTE is negative the feedback functions resemble those for interval schedules at very low rates but become essentially linear thereafter. When RTE=0 s, the schedule is an interval schedule, and when RTE is positive, the feedback functions are bitonic. Feedback functions for the time-based (i.e., s=0) space are not shown as they are all simply straight

Figure 2. Some feedback functions from within the experimental domain. X-axis: response rate in 0.005 s units; Y-axis: reinforcers per second. The "e" and BI parameters were held constant (e = e, BI = 60 e) while RTE was equal to 0, -1, or 1 e.


a=∞, BI=60 s
RTE= −1 s
RTE=0 s
RTE=1 s
Reinforcement
0 04
0 03
0 02
0 01
0 00
0
50
100
150
200
Response Rate (0 005 r/s units)

lines of positive slope where RTE is negative, and of negative slope where RTE is positive. The feedback functions are constant functions when RTE=0. All of the feedback functions from the time-based space have y-intercepts equal to 1/BI. The above description of feedback functions is based on the two equations below:

For schedules where a-->∞,

r=1/[BI+(0.5/R)]-R(RTE)/BI,

and where a-->0,

r=[1-R(RTE)]/BI.

In the above equations, r=rate of reinforcement and R=rate of response. The first equation yields a reasonable, but somewhat oversimplified description. It is based on the notion that the scheduling of reinforcers is the "interval portion" of the schedule described by 1/[BI+(.05/R)] is equally probable at any point during interresponse times (Baum, 1973). Further, this equation is incorrect as BI-->0. Note that as BI-->0 the schedule in effect approaches FR 1 and rate of reinforcement should be equal to R and not what is indicated by the expression (Baum, 1973).

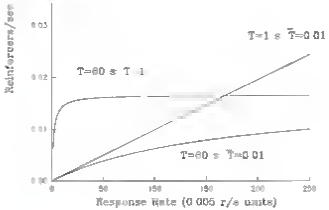
The t-τ System

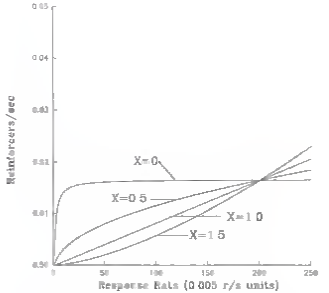
In their seminal paper, Schoenfeld, Cumming, & Hearst (1956) outlined the t-schedule system. In this system, two temporal intervals, t^0 and t^1, alternated. Typically, reinforcers could only occur for the first response in t^0, and not at all in t^1. It was also typical of early research for these temporal parameters to be constant within an

experimental phase (But see Millenson, 1959). Either the total cycle time, T, (t^p+t^e) was held constant and the proportion of the total cycle that was comprised of t^p, (or $\overline{T}$) was manipulated or vice versa. By manipulating just these variables it is possible to arrange a continuum in which lie FI ("by the clock") and random-ratio (RR) schedules (Brandauer, 1958). An FI "by the clock" is a schedule in which a new interval starts timing as soon as the previous one "times out" instead of when the reinforcement cycle ends. A random-ratio schedule is one in which each response has some probability, p, of reinforcement. Figure 3 (top panel) shows feedback functions associated with some different parameters in the t-schedule system.

The t-τ ("tee-tau") system was similar to the t-system except there were two temporal intervals which were superordinate to t^p and t^e. That is, t^p and τ^e alternated, and within each of these intervals t^p and t^e alternated. Any response which coincided with a t^p period was reinforced. (As opposed to just the first response.) The other stipulation was that during τ^p, the duration of t^p must be greater than in τ^e. From its inception the t-system was an ambitious project, its progenitors having as their goal the integration of ratio and interval schedules and simultaneously the establishment of a classification system. Although Schoenfeld et al (1956) based their integration of ratio and interval schedules on a molecular view, they

Figure 3. Some feedback functions from the T- and interactive schedule systems. The top panel shows feedback functions from the T-schedule system and the bottom shows feedback functions from the interactive schedule system. X-axes: response rate in 0.005 s units; Y-axes: reinforcers per second. The parameters of each schedule used to generate the feedback functions are indicated in each panel.


Reinforcers/sec
0.03
0.02
0.01
0.00
T=1 s T=0.01
T=60 s T=1
T=60 s T=0.01
0
50
100
150
200
250
Response Rate (0.005 r/s units)


Reinforcers/sec
0.05
0.04
0.03
0.02
0.01
0.00
X=0
X=0.5
X=1.0
X=1.5
0
50
100
150
200
250
Response Rate (0.005 r/s units)

succeeded in creating a systematization which can be appreciated apart from its assumptions at the controlling-variable level. The relation between what has been referred to as the "independent-variable approach" and the positions taken by researchers in the t-τ system is, however, an extremely complicated one. First, there is Schoenfeld et al.'s (1956) adherence to the molecular controlling-variable approach which prevented them from embracing the independent-variable approach. Later, however, Schoenfeld and Cumming (1963) modified the t-τ system to create the t-τ system in order to remedy a "contaminat[ing]" (p. 757) of "independent and dependent variables," showing that they were aware of the issue. Schoenfeld and Cumming (1960) claimed that reinforcing only the first response is t" was where the independent and dependent variables were contaminated since one had to make reference to responses. There was, however, nothing confounded about the t-τ system. The independent variable are the rules specified by the experimenter and the rules may be programmed independent of behavior. One must measure responses in order to instantiate the rule that "the first response after some period of time will result in food delivery" but this is not a contamination, confounding or confusing of independent and dependent variables. One would be confusing dependent and independent variables if one arranged a VR 60 schedule and claimed one was actually arranging whatever rate of reinforcement ultimately prevailed under this schedule. In

discussing the conceptual origin of τ schedules later, Schoenfeld and Cole (1972) did not make any mention of the "contaminating" of independent and dependent variables, instead referring to the fact that to recognize the first response in t^n was to introduce the ordinal position of responses as an independent variable. Thus, the system seemed no more parsimonious than the traditional classification based on time and ordinal position of responses. This feature was eliminated when the addition of the τ interval allowed every response in t^n to be reinforced but simultaneously allowed traditional schedules to be constructed within the experimental domain.

In addition to t^n and t^a there were other modifications of the original t-schedules. One of these was the inclusion of probability of reinforcement. Responses were, thus, not necessarily reinforced if they met the old kinds of criteria (i.e., first response in t^n in a t-schedule and any response in t^n in the τ-schedules). A probability generator was checked each time a response otherwise eligible for reinforcement occurred and reinforcement was assigned on that basis. This provided, among other things, for a continuum with fixed and variable schedules as points. The t-τ system was made considerably more powerful when a set of concurrently operating variables were arranged. These variables were the same as those already described except that a stimulus could be made contingent on the

nonoccurrence of a response. This allowed for schedules of negative reinforcement to be included in the system.

Interlocking Schedules

It has already been mentioned that points in the schedule space that are not unique kinds of schedules (i.e., FR, VR, VI, continuous reinforcement or FR 1, etc.) are interlocking schedules. Indeed, the schedule-space approach could be called the interlocking schedule system. Virtually all of the interlocking schedules investigated (Berryman & Nevin, 1962; Ettinger, Reid, & Staddon, 1987; Powers, 1968; Rider, 1977) or even proposed (Skinner, 1958) are located within the schedule space.

Although those doing research on the effects of interlocking schedules recognized that they were examining a continuum that united interval and ratio schedules, they were not proposing a new fundamental classificatory scheme. The way interlocking schedules are defined obviously assumes the traditional classification.

A space very similar to part of the fundamental schedule space was proposed by Vaughn (1982). This space was based on combining the contingencies for "linear" interval schedules and ratio schedules. A linear interval schedule is one in which an interval starts timing as soon as reinforcement is "set up" by the preceding interval and not, as in more conventional interval schedules, when the reinforcer is delivered. This type of schedule is referred to as a "linear" interval schedule because the slope of the

feedback function is, in contrast to conventional interval schedules, essentially a constant function except at very low response rates. It should be recalled, however, that the slope of the feedback function for a typical interval schedule is nearly flat over a great range as well (see Figure 2). These schedules are included here with interlocking schedules because they are, essentially, interlocking schedules with the interval portion being of the "linear" type (also called "intervals by the clock"). The difference between Vaughn's schedules and those of the fundamental schedule space relate to the possibility of more than one reinforcer being "set-up." This necessitates the use of a "reinforcement store" variable which is incremented any time an interval expires and decremented when a response occurs (providing the store value is greater than zero). When interval and ratio schedules are run simultaneously (meeting either criteria increments the store) the result is similar to traditional interlocking schedules (RTE<0 and s-->infinity). When the "store" is decremented by a ratio contingency but incremented by the interval contingency, the schedules are very similar to those in the schedule space where RTE>0 (responses add time to the currently scheduled interval) with s-->infinity.

The Interactive Schedule

The interactive schedule (Berger, 1988) is based on the feedback functions for ratio and interval schedules. Its exposition will proceed as in Berger's (1988) paper. The

instantaneous frequency of reinforcement, f, under ratio contingencies, is given below

$f=r/R$

where r is the mean rate of response since the last reinforcer and R is the ratio value having the dimensions responses/reinforcer. The instantaneous frequency of reinforcement available under interval schedules is

$f=1/I$

where I is the interval value having the dimension of minimum time per reinforcer. These equations may be combined

$f=(r/R)^x (1/I)^{1-x}$

Notice that when the exponent, x, is equal to zero, the equation becomes equal to the equation for minimum time per reinforcer and when it is equal to one, the equation becomes equal to the equation for instantaneous rate of reinforcement in ratio schedules. Both R and I may, in the equation above, be replaced by a constant, C, which has the dimensions

$[(\text{responses}^x)(\text{time}^{1-x})]/\text{reinforcer}$.

This then yields the equation

$f=r^x/C$

This is equivalent to holding the values of R and I equal, despite their different units; for example, 50 responses/reinforcer and 50 s. The variable x is not limited to values between 0 and 1 but may take any value. The feedback functions generated when x is varied are

displayed in Figure 3 (bottom panel). The continuum beginning with interval schedules and ending with ratio schedules like between 0 and 1, inclusive. Negative values of x produce a bitonic feedback function, and values greater than 1 produce a function whose first derivative is increasing.

While Berger emphasized the use of the interactive schedule in evaluating "economic" theories, he said many things that are consistent with the independent-variable view expressed here. First, he uses the terms "dependent" and "independent" variables in a fashion consistent with their usage here. He writes (p. 79), "What is needed is a schedule in which both the number of responses per reinforcer and the rate of reinforcement may be dependent variables related to behavior, and in which *the relationship among them is specified exactly as an independent variable*" [emphasis mine].

In deference to the author's treatment, Berger's exposition was presented above, but this should not be construed as an endorsement of everything he has written. It is not clear, for example, that "responses per reinforcer" possesses dimensionality; if rate of response has the dimensions cycles/time, and rate of reinforcement has the dimensions cycles/time, then responses/reinforcer has the dimensions cycles/cycles, and the units cancel. More importantly, Berger's description of the interactive schedule is somewhat inconsistent with his description in

terms of feedback functions. Indeed, his description was altered in order to plot the feedback functions displayed in Figure 3 of this paper. The problem is that the feedback function at x=0, given by Berger's equation, is a constant function (i.e., the feedback function for a time schedule). This is inconsistent with his assertion that all reinforcers must be immediately preceded by responses. This problem is, however, eliminated by adding a term to C. That is, $[0.5/(\text{rate of response})]^{1*}$.

In fairness to Berger, it should be pointed out that he describes 1/t as *minimum* time per reinforcer, which is correct, but this does not change the fact that the equation, when x=0, does not accurately give rate of reinforcement. Had Berger treated this issue more rigorously, he would have been led, perhaps, to another continuum, such as that defined by a, which includes both time schedules and interval schedules. As it stands, Berger's equation is more relevant to the space which includes time and ratio, but not interval, schedules.

Rachlin's Approach

Although Rachlin (1978) was not interested in creating a new type of schedule, his speculation on the nature of empirical feedback functions could lead to the creation of an interesting schedule space. His position seems to have been that if one varies schedule type (VI, VR, VT), the empirical feedback functions will be described by the equation

$C = sI^{m}$

where C is the time spent consuming the reinforcer, I is the time spent responding, m is an exponent which changes with schedule type, and s (unrelated to the s parameter of the schedule space) is a parameter which is related to schedule parameter (e.g., VI 60 s vs VI 30 s). At one point, Rachlin implies that what he is presenting could be used to create a schedule. He writes (p. 348), "variation of a single parameter, m, . .changes the schedule from variable time (at m=0) to variable interval (0<m<1.0) to variable ratio (at m=1)." Given the overall context of Rachlin's (1978) paper, it is likely that what he meant was that m is the parameter of the empirical feedback function that would change as one changed the schedule-type. It is likely, however, that one could arrange a schedule which had the theoretical feedback function characteristics associated with the equation given above. One could, for example, utilize the method of McDowell and Wixted (1986) whereby feedback functions are directly arranged.

A Comparison of the Systems

Scope and Purpose

With the exception of the interlocking schedule "approach," all of the systems suggest a set of schedule parameters--and hence a classification system--that is more fundamental than the traditional one. The t-t, interactive, and schedule space approaches are very similar. All three are vitally concerned with the interval-ratio continuum--at

least as a point of departure. Many writers in the t-t system tradition were trying, at least at first, to encompass as many traditional schedules as possible (Schoenfeld, Cumming & Hearst, 1956) Schoenfeld and Cole (1972) later tried to downplay the importance of encompassing traditional schedules, even arguing that a strength of the tau system was that it did *not*, at least as easily as the t-schedules, encompass the traditional schedules. This later position, however, merely shifted the focus to incorporating more behavioral processes; the introduction of a parallel system in which events were contingent on "not responding" allowed for avoidance behavior (Sidman, 1953) to be produced as well as for the delivery of response-independent events This latter feature was not seen as merely "adding time schedules" to those already embraced by the system, but as evidence that the t-t system could encompass Pavlovian as well as operant kinds of operations. In terms of scope, then, the t-t system and the schedule-space approach are similar. Although Berger (1988) did not seem to have an all-encompassing system in mind, the interactive schedule approach could be easily expanded If, in fact, the interactive schedule were based on response-independent schedules, the a parameter could be added to it and the approach would be very similar in scope and structure to the schedule-space approach

It would be futile to attempt to encompass every kind of schedule within a system in the same sense that ratio and interval schedules may be encompassed. None of the systems, for example, can produce schedules that are identical--at least at the level of independent variables--to Sidman avoidance (Sidman, 1953). All of the systems could, however, produce avoidance schedules that are useful experimentally (in the sense of being capable of generating robust avoidance behavior) and perhaps more useful theoretically. These systems are, thus, "all-encompassing" not because they can embrace all possible extant schedules but because they can embrace many behavioral processes within the same schedule type.

Feedback Functions

Although there are similarities among the systems discussed, they arrange different feedback functions even where the contingencies appear similar. In general, the feedback functions produced by the t-t and interactive schedules are more similar to each other than either is to those produced by the schedule space. As can be seen in Figure 2, feedback functions associated with schedules which lie in the schedule-space continuum from interval to ratio resemble interval schedules at low rates, and then rather suddenly become equivalent to ratio-schedule functions. The functions intermediate to interval and ratio schedules generated from within the t-t and interactive schedule systems (Figure 3) do not rise as fast at low rates of

response and are negatively accelerated over a wide range of response rates.

Response Rate

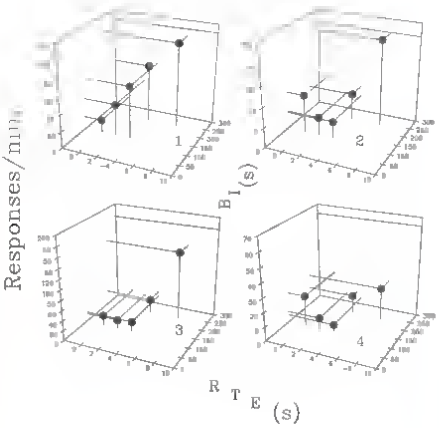
The kinds of data of interest to those who investigated interlocking, interactive, and t-r schedules were typically rate of response and sometimes post-reinforcement pause (PRP). These researchers were also interested in dynamic characteristics of the cumulative records, such as the extent to which they displayed "break-and-run" patterning.

Most of the data of relevance to the interval-ratio continuum have been collected within the t-schedule tradition. In these experiments T was held constant while $\bar{T}$ was systematically varied (Hearst, 1958; Schoenfeld & Cumming, 1960; Schoenfeld, Cumming & Hearst, 1956) or vice versa (Cumming & Schoenfeld, 1959, Schoenfeld, Cumming and Hearst, 1956). Schoenfeld, Cumming, and Hearst (1956), for example, using pigeons as subjects, held $\bar{T}$ constant at .05, and varied T from 30 a to 0.94 s (Experiment 1) and held T constant and varied $\bar{T}$ from 1.00 to .013 (Experiment 2). While numerical data were not presented, inspection of cumulative records reveals that response rate increased as $\bar{T}$ decreased as well as when T decreased. Subsequent direct and systematic replications of these experiments confirmed these findings and elucidated the character of the functions relating response rate to these variables. Schoenfeld and Cumming (1960) summarized the findings from these kinds of experiments in the form of response rates averaged across

subjects at each condition. These they plotted as functions in the 3-d space depicting rate of response as a function of $\overline{T}$, and T. It is clear from this figure that response rates tended to rise rather sharply as $\overline{T}$ was decreased at all but the longest (30 min) T value, and this rapid increase began at higher $\overline{T}$ values when T was short. Rate of response reached a peak and then declined as $\overline{T}$ was decreased. While the data were averaged across subjects, they portray the shapes of the individual functions with reasonable accuracy.

There have been only a few studies of the interval-ratio or time-ratio continuum from within the framework of interlocking schedules. Berryman and Nevin (1962) examined interlocking FR 36 FI n, and FR 72 FI n, where n was either 120 or 240 s. In addition to each of these four conditions, rats were also exposed to FI 120 s and FR 36. Figure 4 shows the results from this experiment recast in the dimensions defined here (RTE and BI; unless otherwise stated, "parameter" will refer to the parameters defined here). The data from the FI 120 s condition are plotted at RTE=0 and BI=120 s. The data for the interlocking schedules appear along two lines parallel to the x-axis (RTE)--one at BI=120 s, and one at BI=240s (corresponding to the FI components of their interlocking schedules). The data from the FR 36 condition are shown as a horizontal line across the "back" plane. This is to remind the reader that the data from the FR 36 condition should actually be plotted at a point where BI→∞.

Figure 4. Response rate as a function of RTE and BI for rats in Berryman & Nevin (1962). The "s" parameter was equal to .8. The subject numbers appear in each panel. The response rate for FR 36 is shown as a horizontal line on the "back" plane of each panel. No point is plotted for the ratio-schedule data in order to remind the reader that such a point does not lie in the space segment shown. The lines which extend from each point parallel to the axes give the three coordinates of the points. X-axes: RTE value in seconds; Y-axes: responses per minute; Z-axes: BI value in seconds. Note that the directionality of the RTE axis is reversed from that in Figure 1.


Responses/min
1
2
3
4
B I (s)
R T E (s)

The translation from traditional schedule terminology to these dimensions is simple; the BI parameter is equal to the interval component (or in an experiment to be considered below, the time component) and the RTE value is given by: RTE=-1[BI/initial ratio value]. The RTE value for a ratio schedule is -1[BI/(desired ratio value-1)]. Notice that the BI value for a ratio schedule only *approaches* infinity--it can always be assigned some value. To arrange a ratio schedule using these parameters it is only necessary to assign BI a very large value such that reinforcement would essentially never be "set-up" independent of behavior.

Herryman and Nevin's (1962) experiment provides data which allow for comparison of schedules that differ in only one parameter. Some of these data are, however, difficult to interpret since Herryman and Nevin did not provide a description of variability. The following description of the data will ignore this fact, but it will be taken up in the Discussion section.

For one subject (Rat 1) rate of response increased as an inverse function of RTE value at both BI values (120 s and 240 s). For the other three subjects this relation was true only at BI=240 s. For 2 of these 3 subjects (Rats 2 and 4) rate of response was a direct function of RTE at BI=120 s and for the third (Rat 3) rate of response did not change as a function of changes in RTE at BI=120 s. For all 4 subjects rate of response was highest under FR 36 but for 2 of the 4 (Rats 1 and 2) the difference in rate of response

between FR 35 (and RTE=-6.667), BI=240 s (the condition which produced the second highest rate of response in all four subjects) was negligible. For Rats 3 and 4, FI 120 s (RTE=0, BI=120 s) produced the third highest rate of response. Berryman and Nevin's data also allow a comparison of conditions which differed only in the BI parameter (RTE=-3.33, BI=120 s or 240 s). For all four rats average rate of response was higher under the BI=240 s condition but substantially so only for Rat 4. Thus, for all four rats rate of response was an inverse function of RTE at BI=240 s. At BI=120 the situation was more complicated, but there is reason to believe that these data cannot be meaningfully interpreted (see Discussion). Where comparisons between BI 120 and 240 s at a fixed RTE value were possible the data suggest that rate of response was essentially the same except for Rat 4 whose data were the most disorderly (see Discussion).

Powers (1966) exposed 2 rats to interlocking FR 32 FT s s where n ranged from 5 to 50 s for one subject and 5 to 80 s for another. For both rats rate of response increased abruptly as n was raised from 5 to 14 s and increased only slightly as it was raised further. In addition to these conditions the subjects were exposed to FR 16.

Figure 5 shows rate of response from this experiment in all of the conditions. Rate of response is plotted as a function of RTE and BI, and data from the FR 16 condition are plotted as a horizontal line on the back panel. For

Figure 5. Response rate as a function of RTE and BI for rats in Powers (1958). The "s" parameter was equal to 0 s. The subject numbers appear in each panel. The response rate for FR 16 is shown as a horizontal line on the "back" plane in each panel. No point is plotted for the ratio-schedule data in order to remind the reader that such a point does not lie in the space segment shown. The lines which extend from each point parallel to the axes give the three coordinates of the points. X-axes: RTE value in seconds; Y-axes: responses per minute; Z-axes: BI value in seconds.

Responses/min
R5
R7
R T E (S)
B I (S)

both rate the manipulations constitute, roughly, a diagonal movement through the independent variable space. The term "diagonal" will be used throughout to indicate that both BI and RTE are changed. For most of the studies discussed, points representing the schedules in an RTE X BI plane fall roughly on a line which is not parallel to either axis.

Rate of response increased abruptly as a function of this diagonal movement but very little after a certain point. For Rat 5 there were, essentially, only 2 different stable states observed in the experiment. For Rat 7, rates intermediate to the highest and lowest ones observed. For both subjects, rate of response under FR 15 did not differ substantially from the highest rates shown in Figure 5 under interlocking schedules.

Rider (1977) exposed rats to interlocking FR 150 FI 300 s and matching VI and VR schedules. That is, the number of responses during each interreinforcement interval occurring during the last 5 sessions of exposure to the interlocking schedule were recorded. These values were randomized and used to prepare a VR tape which controlled the VR sessions. During a subsequent exposure to the interlocking schedule an analogous procedure was carried out on the time between reinforcers and used to construct a collection of VI intervals. All of the rats were first exposed to the interlocking schedule followed by the matched VR schedule. A subsequent return to the interlocking schedule was followed by a matched VI schedule and then a return to the

interlocking schedule. For all three subjects rate of response was highest under VR and lowest under VI. Rates were intermediate under the interlocking schedule.

Figure 6 shows rate of response under one of the interlocking schedule conditions, one of the matched VI conditions, and one of the VR conditions, plotted as a function of RTE and RI. Rate of response did not differ substantially upon redetermination. The data from the matched VR condition are shown as a horizontal line across the "back" plane. The schedules in this experiment, too, represented a diagonal movement thorough the independent variable space.

Ettinger, Reid, and Staddon (1987) exposed rats to three sets of interlocking FR FI schedules in which the initial ratio (IR) value (64, 32 or 16) was constant within a set of conditions and the FI value was changed. The experiment was, thus, similar to Powers (1968) and Berryman and Nevin (1962). In the Ettinger et al. experiment, however, the same five RTE values were used (-0.54, -1.08, -1.37, -2.13, and -3.03 s) for each set of conditions. Ettinger et al. (1987) defined interlocking schedules in terms of the initial ratio value and responses subtracted per unit time rather than in terms of the initial ratio and interval values. Responses subtracted per unit time is equal to -1/(RTE) where RTE has the same units. Each set of conditions represented "equi-slope" manipulations; that is, within each set of conditions, the first derivatives of the

Figure 6. Response rate as a function of RTE and BI for rats in Rider (1977). The "s" parameter was equal to ∞ s. The subject numbers appear in each panel. The response rate under the ratio conditions is shown as a horizontal line across the "back" plane in each panel. No point is plotted for the ratio-schedule data in order to remind the reader that such a point does not lie in the space segment shown. The lines which extend from each point parallel to the axes give the three coordinates of the points. X-axes: RTE value in seconds; Y-axes: responses per minute; Z-axes: BI value in seconds.

Responses/min
R1
R2
R3
RTE (s)
BIT (s)

feedback functions were identical (except at very low rates). The feedback functions were not, however, otherwise identical. Rate of reinforcement was higher, given the same rate of responding, where BI was small and RTE was closer to zero.

Figure 7 shows average rate of response as a function of BI and RTE for the four rats in the Ettinger et al. (1987) experiment. Points are connected if they are from the same set (equal initial rates and thus equi-slope) or if they have the same RTE value (five sets of triplets). As the absolute value of RTE was increased in conjunction with increases in BI value, response rate tended to increase. Most of the functions from equi-slope schedules depicted in Figure 7 are negatively accelerated or s-shaped. Response rate also tended to increase solely as a function of changing the BI value. For all four rats, schedules having an initial ratio (IR) value of 16 produced the lowest rates of response in comparison with the other schedules (at the same RTE value). For three of the rats, IR 32 schedules produced rates intermediate to those with IR values of 16 and 64 (at the same RTE value). For the other subject, rates of response maintained by IR 32 and 64 schedules were not different.

The data from Powers (1968), Nider (1977), and Ettinger et al. (1987) suggest that a diagonal movement through the independent-variable space (RTE decreases as BI increases) results in increases in rate of response irrespective of the

Figure 7. Response rate as a function of RTE and BI for rats in Stringer et al (1987). The "s" parameter was equal to = s. The subject numbers appear in each panel. X-axes: RTE value in seconds, Y-axes: responses per minute; Z-axes: BI value in seconds.

Responses/Min
1
2
3
4
IRT (s)
RTE (s)

a parameter. In Rider's (1977) and Ettinger's experiments, s was equal to infinity (VI base), while in Powers' experiment, s was 0 (VT base). Quantitative assessment of the effects of manipulating s are, however, difficult since no experiment to date manipulated this parameter, and between-experiment comparisons are difficult since the levels of SI examined were quite different in these two experiments.

Of the 4 experiments in the interlocking-schedule tradition reported here, the data from Berryman and Nevin's (1962) experiment are the most enigmatic. In general, their data are consistent with the generalization that a diagonal movement through the space results in increases in rate of response. Some of the data, particularly for Rats 2 and 4, are, however, somewhat difficult to understand. It is not clear why RTE=0 s, SI=120 s (FI 120 s) should have maintained higher rates (substantially higher in the case of Rat 4) than under conditions where SI equalled 120 s, and RTE was negative. This outcome is, perhaps, not unlikely where RTE is negative and its absolute value approaches SI, since such schedules would resemble very small ratio schedules. This, however, was not the case in Berryman and Nevin's experiment. It is much more likely that this outcome had more to do with the order in which the schedules were imposed. The FI 120-s schedule was the last one imposed and followed the FR schedule.

The above summary of what is currently known about the space is not quite complete. There has been relatively intensive investigation of schedules which lie at some limits, especially where RTE=0 and s-->∞. Manipulation of BI where RTE=0 and s-->∞ constitutes a parametric analysis of interval schedules. It is generally accepted that the function which relates response rate to BI value under these circumstances is of negative slope (Catania & Reynolds, 1968). That is, rate of response decreases as the interval value is increased. The amount of the decrease is, however, greater at higher BI values. When response rate is plotted as a function of rate of reinforcement the more familiar positive-sloped "input-output function" is produced. It should be made clear that the range of schedules for which this function is appropriate is limited. That is, as the BI value approaches zero, the schedule approaches an FR 1 schedule and rate of response decreases (Baum, 1993).

Parametric manipulation of ratio schedules is comparatively rare. In general, however, it seems clear that rate of response eventually decreases as a function of ratio value in both fixed-ratio (Boren, 1953; Felton & Lyon, 1966) and random-ratio (Bass, 1993; Brandauer, 1958). It is also clear that response rate first increases rapidly as the ratio is raised from FR 1 (Baum 1993; Boren, 1953; Brandauer, 1958). For most of Baum's (1993) pigeons, rate of response was roughly constant over RR values from about 8 to about 64, after which response rate declined rather slowly.

Baum (1993) failed to maintain responding at ratio values over 512--less for most of the pigeons. This bitonic function probably characterizes all kinds of ratio schedules but data on the issue are difficult to find. Ratio schedules occur when RI approaches infinity. The ratio value minus one (once responses subtract enough time off of the currently scheduled interval, there is still one more response required, at least when one is arranging ratio schedules where s-->infinity) is then given by -1(RI/RTE).

There have also been a reasonable number of studies examining the effects of time schedules (i e., s=0) and comparing them with the effects of schedules of response dependent reinforcers. Typically, time schedules maintain lower rates of responding than response-dependent schedules (i.e., s-->∞), and responding may even cease altogether (Burgess & Wearden, 1981; Catania & Keller, 1981; Lattal, 1972, 1974; Zeiler, 1968). It is probably true that FT schedules do not produce as rapid and complete a decrement as VT schedules, especially when compared to fixed vs. variable intervals (Lattal, 1972). Finally, some characteristics of the behavior maintained by response-independent schedules may depend on the kind of response-dependent schedules to which the subjects have been exposed (Burgess & Wearden, 1981).

There have been no studies examining what has been referred to here as the s parameter (except at the endpoints). Lattal (1974), however, investigated the

effects of different proportions of VI and VT ranging from 0 to 1.0 and found that rate of response increased as a function of the percentage of the reinforcers that were response dependent. For all 5 pigeons, the function was either negatively accelerated or s-shaped. This experiment bears some relationship to examination of the s-parameter in that both represent a continuum between time and interval schedules.

Some additional points in the space have been investigated, namely, RI=infinity s and RTE=0 s ("extinction") or RI=infinity s and RTE=infinity s (FR 1). When all of the data known so far are considered some assertions may be made as to the overall shape of the two 3-d spaces which result when s is either 0 or infinity s. The 4-d space which results when the s parameter is continuously varied cannot, of course, be depicted by conventional graphic means. Discussion of the shapes of these spaces will be deferred to the Discussion section.

The data from one further set of schedules requires discussion; that is, data from "linear VI schedules with ratio subtraction" (Ettinger, Reid, & Staddon, 1987; Vaughn 1982; Vaughn & Miller, 1984). These researchers exposed subjects to linear VI schedules with FR subtraction. These schedules work the same as the interlocking-schedules based on linear VI-schedules discussed above, except that the "reinforcement store" is decremented (but the reinforcer is not delivered) by 1 when the ratio contingency is met

Ettinger et al., using rats, investigated VI values of 30, 45, 60, and 90 s with FR 15 and 20 (for each subject) and Vaughn (1982), using pigeons, investigated VI values of 30, 45, and 60 (for each subject) with either FR 20, 40, or 60 (3 groups of 3 pigeons each). In addition, Vaughn exposed his pigeons to linear VI schedules whose rate of reinforcement equaled that under each subtraction-schedule (See Vaughn & Miller, 1984, for these data). With the exception of the matched VI schedules in the Vaughn (1982) study, the manipulations in these two experiments fall along a diagonal in the two-dimensional schedule space formed by RI value and RTE; that is, when the RI value was increased, the RTE value was increased. The translation of Vaughn's (1982) schedule terminology into RI and RTE is: RI=VI, and RTE=VI parameter/FR subtraction value. The feedback functions for schedules with positive RTE values are bitonic. An example is given in Figure 2. Recall that the schedules investigated in these two experiments were based on "linear" interval schedules and so the function is not continuously differentiable at the maximum as it is in the function shown in Figure 2 (i.e., there is not a smooth transition between the ascending and descending limbs of the function). In the two experiments described above, equal FR subtraction values produce feedback functions that have the same slope for the descending limb.

Comparing data from within a set of equal-slope schedules (FR subtraction value was the same) rate of

response tended to be highest where BI and RTE were smallest and lowest where BI and RTE were largest. Figures 7 and 8 show response rates taken from figures in, respectively, Ettinger et al (1987) and Vaughn and Miller (1984) and plotted in terms of BI and RTE. The left- and right-hand panels of each pair of panels in Figure 8 shows response rates from under, respectively, schedules with FR subtraction-values of 15 and 20. The left-hand, middle, and right-hand columns of Figure 9 show response rates from, respectively, schedules with FR subtraction values of 20, 40, and 60.

The subjects in Ettinger et al 's experiment were exposed to more than one set of equi-slope schedules and, therefore, within-subject comparisons are possible. There was no consistent relation between the two data sets. For two of the four subjects, rates of response were about equal in the two sets, and for the remaining two subjects there tended to be a small difference between the two in terms of rate of response but in opposite directions. In the Vaughn (1982) study, subjects were exposed to only one set of equi-slope schedules and therefore only between-subject comparisons are possible. Rates of response tended to be lowest for subjects exposed to the schedules producing the steepest negative slopes (i.e., under the FR 20 subtraction value) and highest under schedules producing the shallowest negative slope (i.e., under the FR 60 subtraction value).

Figure 8. Response rate as a function of RTB and BI for rats in Ettinger et al. (1987) under "linear VI with ratio subtraction" schedules. The "a" parameter was equal to ∞ s. Each subject's data are presented in two different panels; the left-hand panel showing response rates relevant to schedules with a subtraction value of 15, and the right-hand panels show response rates from schedules with a subtraction value of 20. The subject numbers appear beside the pairs of panels. The subjects whose data are depicted in this figure are not the same as those whose data are depicted in Figure 7. X-axes: RTB value in seconds; Y-axes: responses per minute; Z-axes: BI value in seconds.

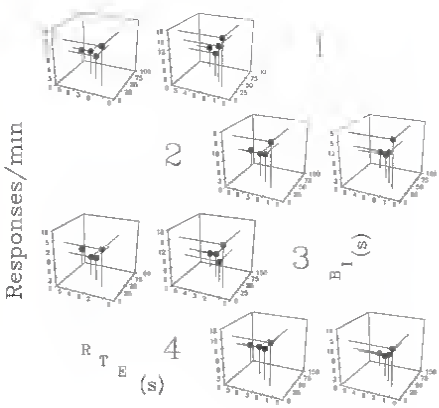

Responses/min
RT (s)
BI (s)
1
2
3
4

Figure 9. Response rate as a function of RTE and BI for rats in Vaughn and Millar (1984) under "linear VI with ratio subtraction" schedules. The "a" parameter was equal to " a ". The subject numbers appear above each panel. Data from schedules with ratio subtraction values of 20, 40, and 60 appear, respectively, in the left-hand, middle, and right-hand columns. X-axes: RTE value in seconds; Y-axes: responses per minute; Z-axes: BI value in seconds.

Responses/min
19
150
95
93
140
52
47
94
279
RTE (s)
BI (s)

Comparisons of rates of response maintained by the FR subtraction schedules and the matched linear VI schedules (Vaughn, 1982) revealed few regularities between-subjects. About all that can be said is that there appeared to be some tendency for rates of response under the matched VI schedules to be equal to, or greater than, the rates maintained under the subtraction schedules to which they were matched. For 6 of the 8 subjects, the highest rates of response were produced by the "richest" linear VI schedules. These comparisons are, however, somewhat complicated by the fact that no indications of variability were provided.

Berger (1966), investigating his "interactive schedule," $f=x^2/C$, held C constant and manipulated x. Half of the 6 subjects (rats) were first exposed to x=1.0 and x was decreased across phases to 0.7, 0.3, and 0.0. The other half of the subjects were exposed first to x=0.0 and x was subsequently increased to 0.3, 0.7, and 1.0. (One subject in the latter condition was not exposed to x=1.0.) For all of the subjects rate of response tended to be a fairly linear function of x but subjects differed in their sensitivity to this variable. For all of the subjects exposed to x=1.0 rate of response was higher than it was at x=0.0. Regression lines fit to each subject's data show that the three smallest slopes occurred for animals in the condition in which x was increased across phases.

It has been suggested Baum (1973, 1966) that ratio schedules maintain higher rates than interval schedules

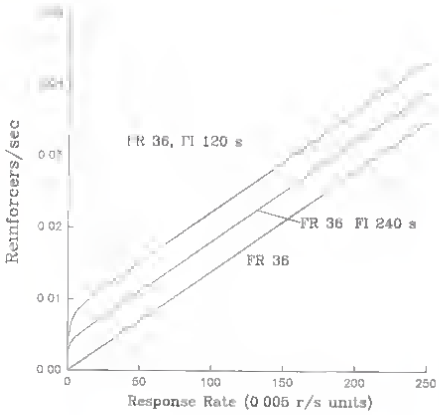
because the correlation between rate of response and rate of reinforcement is greater in ratio schedules. While the first derivative of an interval-schedule feedback function is large at low response rates, it is negligible at higher rates, while the derivative of a ratio-schedule feedback function is a constant much greater than zero ("much greater than zero" relative to the first derivative of interval schedule feedback functions at all but very low rates of response). This view is typically known as a "molar" view and frequently associated with the notion that rate of response is some function of rate of reinforcement (though the former statement emphasized the derivative of the feedback function rather than its value). The "slope" explanation of interval-ratio differences cannot be applied with success to the data described above. While it nicely characterizes the data from most of the t-tau schedule experiments and from Berger's interactive schedule experiment, it cannot explain why response rates should increase after the implementation of schedules which result in decreases in rate of reinforcement as well as no change in the slope of the feedback function. This condition results when the FR component of an interlocking schedule is held constant and the interval component is increased. Powers (1963), Berryman & Nevin (1962), and Ettinger et al. (1987) provided data relevant to this issue. In an attempt to summarize these and other data it is tempting to say that higher rates of response will be associated with schedules

having feedback functions more like those of ratio schedules. Figure 10 shows three feedback functions; FR 36, and interlocking FR 36 FI 120 s and FR 36 FI 240 s. This figure, thus, represents some of the contingencies investigated by Berryman & Nevin and illustrates that as the interval component of interlocking schedules is increased the feedback function associated with the schedules become progressively ratio-like. Consistent with the above theory, increases in rate of response occurred when the interval component was increased. It is not clear, however, that the theory is applicable to the results from parametric manipulation of VI and VR schedules which lie at the limits in all three spaces.

Temporally Local Features of Behavior

The extent to which behavior resembled either interval or ratio "type" behavior was of central importance to most of the researchers examining the t-τ, interlocking-schedule, and interactive-schedule approach. Since interval and ratio schedules--especially fixed-interval and fixed-ratio--were, and still are, generally thought to produce distinctive temporal patterns of responding, temporally local features of behavior, such as the post-reinforcement pause, and the characteristics of the post-pause responding were examined. Most of the data comes from t-tau schedule research. Schoenfeld and Cole (1972), in their review of the t-τ literature, presented data which suggest that the change in patterning from interval to ratio type occurs at the same

Figure 10. Feedback functions for FR 36 and two interlocking schedules which have FR 36 as their ratio base. The interval base was either VI 120 or 240 s as indicated in the figure. X-axis: response rate in 0.005 s units; Y-axis: reinforcers per s.


Reinforcers/sec
0 03
0 02
0 01
0 00
0
50
100
150
200
250
Response Rate (0 005 r/s units)
FR 36, FI 120 s
FR 36 FI 240 s
FR 36

values at which rate changes. Figure 2-6-c (p. 30) of their book (Schoenfeld & Cole, 1972) shows cumulative records from an experiment in which T was held constant at 120 s and $\overline{T}$ varied. At $\overline{T}$= 0.08, rate of responding was barely increased over levels maintained under FI ($\overline{T}$=1.0) and FI type patterning is evident in the cumulative records. Rate of response increased still further at $\overline{T}$=0.004 and at this point pauses are shorter and resumption of responding post-pause is more abrupt. A similar pattern can be seen by comparing Figures 2-6-a and 2-6-f (pp. 32-33). Cumulative records presented by Berryman and Nevin (1962; pp. 218-221) also show this same pattern of change.

Purpose of Experiments

The main goal of the present empirical work was to add to the sparse literature that is immediately relevant to the development of the schedule-space approach (i.e., interlocking schedules) as well as the larger literature relevant to systematization of interval and ratio schedules in terms of independent variables. The research is intended, however, to have relevance to the other kinds of approaches to schedule-controlled behavior, i.e., the controlling-variable approach as it has been described here. This includes both molar and molecular approaches.

To date, only interlocking schedules based on fixed parameters have been investigated. One immediate way to supplement the literature is to investigate the properties of interlocking VI VR and VR VT schedules. Thus, in the

experiments reported here, BI was based on 40 intervals generated by Catania and Reynold's (1968) constant probability equation.

Virtually all of the literature on interval-ratio continua concerns experiments in which one of the independent variables is held constant and the other manipulated. This is reasonable but it has the disadvantage, perhaps, of making the data less immediately relevant to other kinds of systematization strategies. In the experiments described here, many of the schedule changes were constructed so that rate of reinforcement and number of responses per reinforcer were held constant at the time of the change in conditions. This strategy, perhaps, has relevance to both molarism and molecularism (Ferster & Skinner, 1957). Ferster and Skinner (1957) maintained the keypecking of two pigeons under VI schedules and thus changed the schedules to VR schedules which were matched to the preceding VI schedules in terms of number of responses per reinforcer. (This experiment immediately preceded Ferster and Skinner's "yoked box" experiment.) Such a manipulation results in no change in rate of reinforcement provided that rate of responding does not change. One bird stopped responding but the other bird's rate of response increased. Ferster and Skinner recognized the latter as the more likely outcome. They argued that the response was not well conditioned to begin with in the bird which stopped responding. They knew, further, that keypecking was

typically maintained at VR schedules comparable to the one they imposed. They suggested that an "autocatalytic" process involving rate of reinforcement and rate of response could drive the increase, but that response rates must first increase because of differentiation (p. 400) since rate of reinforcement does not change under these circumstances unless rate of response changes. If this reasoning is sound then the sensitivity of behavior to this kind of contingency change may reveal sensitivity to molecular processes. That is, if such a phase change fails to result in a change in behavior, then the molecular variables which are indirectly arranged must, in some sense, be at sub-threshold levels. From the molarist perspective, on the other hand, such experiments provide a direct measurement of the sensitivity of behavior to the slopes of the feedback functions. Since overall rate of reinforcement was held constant at the time of transition, it must have been the slopes of the feedback functions that were relevant in starting the behavior change.

In keeping with the largely defined goal of elucidating the properties of behavior maintained by schedules in the space, one of the purposes of this paper is to describe behavior in as much temporal detail as possible. This includes interresponse-time (IRT) distributions and related data but also attempts to characterize aspects of responding that cannot be revealed when IRTs are aggregated in bins. Such data, too, should have relevance to both molar and

molecular approaches to systematization as well as being the stuff of phenomenological laws.

CHAPTER 2

METHOD

Subjects

The subjects were 6 White Carneau pigeons. The subjects in Experiment 1 were experimentally naive at the beginning of the experiment and these in Experiment 2 had served as subjects in an undergraduate laboratory class. These latter subjects had been exposed to VI and VR schedules in the class. All of the subjects were maintained at approximately 80% of their free-feeding body weight for the duration of the experiment. The pigeons were individually housed, and water and grit were continuously available in the home cage. A pigeon was given supplementary feedings after a session if its body weight was less than the target 80%.

Apparatus

Two standard Lehigh Valley operant-conditioning chambers for pigeons (Model #1519) were used. The chambers were located in a room separate from the controlling equipment. During the first part of Experiment 1 contingencies were arranged and data collected by a PDP-8 computer operating under the Super Sked System (Snapper & Inglis, 1978). During the remainder of Experiment 1 and for

all of Experiment 2, contingencies were controlled, and data collected by a different computer system. Each chamber was connected to a microprocessor (Walter & Palya, 1984) to which BASIC programs were downloaded.

During the portion of Experiment 1 that was controlled by the PDP-8, each response produced a tone, 0.05 s in duration, during which responses could not be recorded. During the remainder of Experiment 1 and for Experiment 2, criterion responses still produced a 0.05 s tone but the criteria changed somewhat due to the programming required to record the temporal locus of each response. A response, under these latter contingencies, always produced 0.14 s during which further responses could not be counted as such. In both experiments, the houselight was illuminated and the center key was transilluminated by a white light. During reinforcement only a light in the grain dispenser was illuminated. Reinforcement was always 3 s access to mixed grain, and sessions were conducted, typically, from 5-7 days a week.

Procedure

Experiment 1

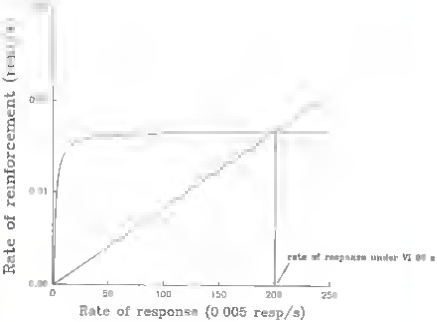
All 3 pigeons were first trained to peck an illuminated key by the method of successive approximations. They were then exposed to a series of small FR schedules, the value of which was increased during a session. When the pigeons were responding reliably under FR 25, the schedule was changed for 1 session to VI 30 s. Before the next session the

schedule was changed to a VI 60 s, and sessions, from this point on, were terminated after 40 reinforcers. The VI 60 s (RI=60 s, RTE=0 s, n=infinity) constitutes the "baseline" in the experiment; subjects were returned to the VI 60-s baseline following every "experimental phase."

An experimental phase always consisted of an increase in the RI value and a decrease in the RTE value (i.e., it became more negative). The parameters were chosen so that the feedback function associated with the new schedule intersected the feedback function associated with the VI 60 s schedule at the point which represented the pigeon's actual rate of response averaged over the final 10 sessions of VI 60 s. An example of this relationship is shown in Figure 11, which depicts feedback functions for VI 60 s and a "matched" VR schedule (RI-->infinity and -1(RTE] is some fraction of RI such that -1(RI/RTE]=the ratio value). If a pigeon responded at an average of x responses/sec (averaged over the final 10 sessions) under the baseline VI 60-s schedule, any parameter (RTE and RI) values satisfying the equality,

n=1/{RI+(.5/60})-[(x*RTE)/RI], could constitute the values of the succeeding experimental phase. Adherence to this procedure insured that overall rate of reinforcement and the number of responses per reinforcer would be the same as the baseline average as long as rate of response did not change. That is, these molar variables were held constant at the initiation of the phase change. In addition to the kinds of

Figure 11 Feedback functions for VI 60 s and for a "matched" ratio schedule. The feedback function for the ratio schedule intersects that for the VI schedule at the point for which the x-axis value equals rate of response under the VI. X-axis: rate of response in 0.005 r/s units; Y-axis: rate of reinforcement (reinforcers per second)


Rate of reinforcement (reinf/s)
0.01
0.00
0
50
100
150
200
250
rate of response under VI 60 s
Rate of response (0 005 resp/s)

manipulations described above, Pigeon 2760 was exposed to a schedule in which responses subtracted time off of the currently scheduled interval, and the amount of time subtracted increased as a function of responding (i.e., the absolute value of RTE was variable and increasing). Specifically, SI was equal to 6000 s, RTE started at -26 s, and the occurrence of each response subtracted an additional 4 s from the previous RTE value (see Table 1). Thus, the first response subtracted 26 s from the currently scheduled interval, the second response subtracted 30 s, the third subtracted 34 s etc. Although this kind of schedule is not located in the 3-dimensional space, it suggests a 4-dimensional space in which the rate of change in RTE as a function of responding constitutes the fourth dimension. This phase was included, but is not emphasized in the ensuing discussion, because Pigeon 2760's response patterning differed somewhat from the other pigeons during interlocking and ratio-schedules. It produced a response pattern for this pigeon that was more like that of the other pigeons (see Results).

Table 1 shows the series of conditions to which each subject was exposed and the number of sessions each condition was in effect.

The conditions shown in Table 1 will sometimes be referred to in terms of their relationship to VR schedules. If a schedule, for example, has a SI value of 120 s, the slope of its feedback function--at the point where it

TABLE 1. CONDITIONS AND NUMBER OF SESSIONS EACH WAS IN EFFECT FOR EXPERIMENT 1

SUBJECT

1087

CONDITION	# of SESSIONS
BI=60 s, RTE=0 s	52
BI=120 s, RTE=-1.0 s	22
BI=60 s, RTE=0 s	48
BI 300 s, RTE=-10 S s	114
BI 60 s, RTE=0 s	approx. 240
BI 3000 s, RTE=-54 s	12 (phase aborted)
BI 60 s, RTE=0 s	47
BI 3000 s, RTE=-45 s	68
BI 60 s, RTE=0 s	136
VR 6I	130
BI 80 s, RTE=0 s	97
BI 3000 s, RTE=- 45 s	97
BI 60 s, RTE=0 s	104
BI 240 s, RTE=- 2.3 s	80
BI 60 s, RTE=0 s	180
BI 120 s, RTE=- 1.1 s	82

Table I--continued

SUBJECT

5994

CONDITION	# OF SESSIONS
BI 60 s, RTE=0 s	128
BI 600 s, RTE=-7.5 s	112
BI 60 s, RTE=0 s	approx 240
BI 3000 s, RTE=-58 s	13 (phase aborted)
BI 60 s, RTE=0 s	45
BI 3000 s, RTE=-70 s	69
BI 60 s, RTE=0 s	138
VR 60	132
BI 60 s, RTE=0 s	181
BI 600 s, RTE=-8.5 s	269
BI 60 s, RTE=0 s	182
BI 240 s, RTE=-2.7 s	182

2760

BI 60 s, RTE=0 s	51
BI 120 s, RTE=-1.2 s	22
BI 60 s, RTE=0 s	53
BI 600 s, RTE=-12.2 s	107
BI 60 s, RTE=0 s	approx. 240
BI 3000, RTE=-69 s	72
BI 60 s, RTE=0 s	152

Table 1--continued

SUBJECT

2760

CONDITION	# OF SESSIONS
VR 43	112
BI 60 s, RTE=0 s	147
BI 6000 s, RTE=-26 s + 4 s/resp.	313
BI 60 s, RTE=0 s	172

intersects the feedback function for the VI 60 s schedule—will be 58% of the feedback function for a matched VR schedule. Some data were misplaced during one of the VI 60-s baseline schedules so it is impossible to tell exactly how many sessions there were during this time period. This is why, in Table 1, the number of sessions is listed as "approximately 240."

Experiment 2

Because the 3 pigeons in this experiment had been trained to peck a key in an undergraduate laboratory class, they were given some adaptation time, allowed to eat from the feed magazine, and to peck the key with each peck resulting in food presentation in the new chamber one or two sessions. They were then given one session of RR 10 (40 reinforcers). The following session began the first phase of the experiment. In this experiment, a was always equal to zero. That is, the bases of these schedules, unlike Experiment 1, were VT schedules. Also unlike in Experiment 1, subjects were not returned to a particular baseline schedule after each experimental manipulation. Unless otherwise indicated, a condition remained in effect until either no trends were observable or when the range of systematic variation (trends) could be ascertained.

During the first portion of this experiment overall rate of reinforcement and number of responses per reinforcer were held constant at the time of a phase change. When rate of response changed, however, the levels of these variables

also changed. This characterization applied to all schedule changes up to the reinstatement of the VT schedule (RTR=0) Table 2 lists the sequence of conditions to which each subject was exposed and the number of sessions that each condition was in effect

TABLE 2. CONDITIONS AND NUMBER OF SESSIONS EACH WAS IN EFFECT FOR EXPERIMENT 2

CONDITION	SESSIONS
SUBJECT 1694	
BI 600 s, RTE=-15 s	246
BI 300 s, RTE=-7.3 s	28
BI 15 s, RTE=0 s	55
BI 3.7 s, RTE=+.4 s	47
BI 15 s, RTE=0 s	52
BI 300, RTE=-7.3 s	69
1404	
BI 600 s, RTE=-15 s	237
BI 300 s, RTE=-7.3 s	30
BI 14.75 s, RTE=0 s	54
BI=5.25 s, RTE=+0.7 s	47
BI 14.75 s, RTE=0 s	51
BI 300 s, RTE=-7.3 s	67
3673	
BI 600 s, RTE=-15 s	240
BI 300 s, RTE=-7.2 s	85
BI 21.1 s, RTE=0 s	57
BI 300 s, RTE=-7.2 s	108

CHAPTER 3

RESULTS

The data from both experiments will be described in terms of 3 different aspects of the data; "steady state," transitions, and higher-order transitions. The expression "higher order transitions" refers to changes in the steady states or transitions which depend on exposure to previous conditions.

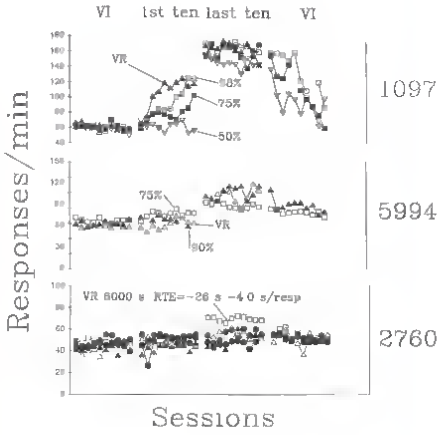
Stable-States

Experiment 1

Overall response rates

Figure 12 shows overall response rates from the last ten sessions of the baseline VI 60 s schedule which preceded every experimental phase, the first and last ten sessions of an experimental phase, and the first ten sessions after each return to VI 60 s. This section will be concerned with the steady states, i.e., the data which are plotted under the headings "VI" (on the left) and "Last ten." For Pigeons 1097 and 5954 there were higher-order transitions; that is, earlier transitions differed from later ones. Data which preceded what appeared to be the higher-order steady state are omitted from this figure. Specifically, for Pigeon 1097, the first 4 experimental conditions and their

Figure 12. Response rate during, from left to right, the last 10 sessions under, VI 60 s, the first and last 10 sessions under experimental phases and the first 10 sessions following the return to VI 60 s. The subject numbers are indicated in each panel. Each condition is identified in the figure in terms of the percent of a matched VR (see Method) except for Pigeon 2760, in which there was little difference between any of the conditions. Y-axis: responses per minute.

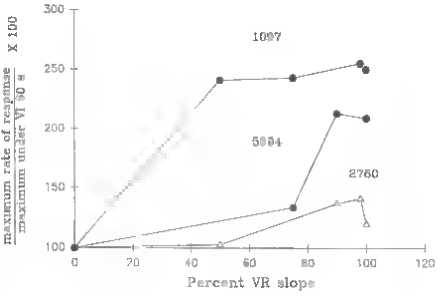

VI
1st ten last ten
VI
VR
88%
75%
50%
1097
75%
VR
80%
5994
VR 6000 s RTE=-26 s -4 0 s/resp
2760
Responses/min
Sessions

preceding baseline phases were omitted, and for Pigeon 5994, the first 3 experimental phases and their preceding baseline phases were omitted (see Table 1).

For Pigeons 1097 and 5994 rate of responding was reliably increased by VR schedules and those "intermediate" to VR and VI. For Pigeon 2760, overall rate of response was not reliably increased with respect to baseline rates except in the condition in which RTE was a function of responding. That is, for this pigeon, even a VR schedule failed to increase response rate. Overall rate of response was, however, increased during some portions of the interlocking- and VR-schedule phases (see Figure 13 below). For the most part, there was little difference between the rates of response maintained by VR schedules and rates under the interlocking schedules. The exception was for Pigeon 5994 under the 75% condition. Although there is considerable overlap in the ranges of rates in all the experimental conditions, rates tended to be lower in this condition compared with VR and the interlocking schedule with a feedback function slope 98% of that of a matched VR. This can be more clearly seen in Figure 13.

Figure 13 shows the relative maximum rate of response which occurred during the steady states depicted in Figure 12, as a function of percent VR slope. Each data point shows the average over one session. The sessions from which the maximum rates were selected include every session in the experimental phase and the last 20 sessions of the baseline

Figure 13. Percent VI maximum response rate as a function of the percent VR under baseline and experimental conditions. X-axis: percent VR (see text for explanation); Y-axis: (response rate under experimental phase/response rate under VI) X 100.


maximum rate of response / maximum under VI 90 s X 100
300
250
200
150
100
1097
5004
2760
0
20
40
60
80
100
120
Percent VR slope

phases. The dependent measure is expressed as a percentage of the maximum rate of response which occurred during the last 20 sessions of the preceding VI schedule.

For all 3 pigeons maximum rate of response was higher under ratio and some interlocking schedules than the maximum attained under baseline conditions. For Pigeons 1097 and 2760 all schedules which produced increases did so to about the same degree. For Pigeon 5394 maximum rate of response under the 75% condition was intermediate to the maximum rate of response observed under baseline conditions and that observed under the 50 and 100% conditions, and for Pigeon 2760 the 50% condition did not produce increases in maximum rate of response. The functions are, therefore, somewhat s-shaped for both 5394 and 2760.

Figure 14 shows maximum rate of response plotted as a function of BI and RTE for all of the phases covered in Figure 12. Maximum rate of response in the VR condition is shown as a horizontal line across the "back" plane of each panel. Although Figure 13 facilitates comparison between the maximum rates produced by the various conditions Figure 14 shows the data in the context of the surface produced when maximum rates are plotted as a function of BI and RTE. The manipulations reveal a diagonal cross-section of this surface. In general, manipulations along this diagonal produced increases in maximum rate of response up to a point where further manipulations no longer produced increases.

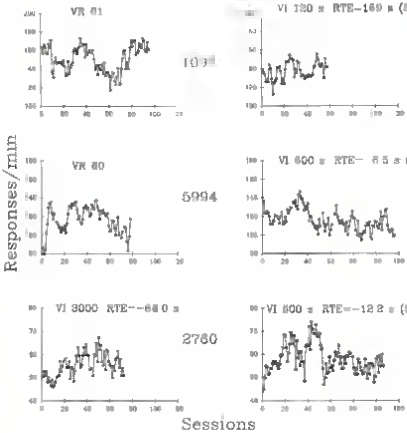
Figure 14. Maximum response rate under baseline and experimental phases as a function of BI and RTE. Maximum rate of response under VR is shown as a horizontal line across the "back" plane of each panel. No point is plotted for the ratio-schedule data in order to remind the reader that such a point is not within the space segment shown. The lines which extend from each point parallel to the axes give the three coordinates of the points. X-axes: RTE value in seconds, Y-axes: maximum rate of response (responses/min); Z-axes: BI value in seconds.

Responses/min
1097
5994
2760
B I (s)
R T E (s)

Only for Pigeon 5994, however, were intermediate rates produced.

Figure 15 shows overall response rates for each session within long segments of some final states for all three pigeons. The sessions depicted are those from the point where session rates of response were no longer rising. That is, they show the entire stable-state. Although the range of response rates observed under these conditions was large, it is not clear that these data are particularly "noisy." That is, it is not clear to what extent the variability is "noise" as opposed to some combination of noise and complex oscillations. Notice that the y-axes of Figure 15 are truncated so as to make variability more evident. Although there are not enough segments nor segments of sufficient length to analyze in detail, the data seem consistent with the latter interpretation, and there is some indication that the character of the oscillations may exhibit some inter- and intra-subject generality. When 5994 first reached what would later prove to be the near maximum rate of response for the phase, for example, there followed a rather symmetrical decline and return to the maximum. This is evident in both of 5994's panels. Pigeon 1097 exhibited a similar pattern. The data for 1097 (VR) and 5994 (VI 600 s, RTE=-# 5 s) are remarkably similar for the first 60-70 sessions following the initial attainment of near-maximum rates. Under both conditions that produced substantial increases for 2760, response rates reached a maximum after

Figure 15. Rate of response as a function of sessions under some experimental phases for all three pigeons. The schedule conditions are indicated in each panel. X-axes: sessions; Y-axes: responses per minute.


VR 61
VI 120 s RTE-189 s (50%)
109
VR 80
VI 600 s RTE- 65 s (80%)
5994
VI 3000 RTE--680 s
VI 600 s RTE=-122 s (90%)
2760
Responses/min
Sessions

about 45 sessions and then began an equally slow decline suggesting the possibility of relatively long-term oscillations.

Molecular description

Figures 16, 17, and 18 show data from the last session of 3 baseline conditions for Pigeons 1097, 5594 and 2760, respectively. The 3 rows of each figure display, from top to bottom, the interresponse time (IRT) distribution, the distribution of reinforced IRTs and the IRTs per opportunity (Anger, 1956). Data in each column come from baseline conditions preceding three different experimental phases. Figures 19, 20, and 21 show these same kinds of data but from the experimental phases which were preceded by the baseline conditions shown in Figures 16, 17, and 18. The distributions show as much temporal resolution as possible. The differences in bin sizes used in these figures reflects the difference in the programming equipment used in the beginning and end of Experiment I. The last session of each phase was chosen for display in order to prevent any selection of specific kinds of distributions.

The distributions which are composed of 0.1-s bins must be interpreted with some caution; an error in data collection caused an unknown amount less than 0.1 s to be added to each IRT. This had an almost imperceptible effect judging from the close similarity between these distributions and those from the latter part of the experiment. The main difficulty is that this tends to blend

Figure 16. Distribution of all IRTS, distribution of reinforced IRTS and IRT/OF functions for the last session under each of 3 baseline phases for Pigeon 1057. The distribution of all IRTS (top panels) and reinforced IRTS (middle panels) are expressed as proportions of the total. Many of the bars in the far right of the IRT/OF functions (bottom panels) are cut off. X-axes: 0.01 s or 0.1 s bins (as indicated in axes labels); Y-axes: relative frequency or IRTS/OF (as indicated in axes labels).

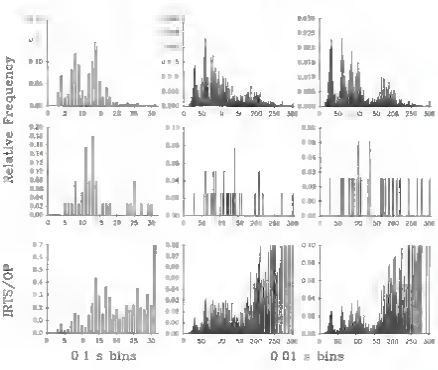

Relative Frequency
IRTS/OP
0 1 s bins
0 01 s bins

Figure 17. Distribution of all IRTS, distribution of reinforced IRTS and IRT/OP functions for the last session under each of 3 baseline phases for Pigeon 5394. The distribution of all IRTS (top panels) and reinforced IRTS (middle panels) are expressed as proportions of the total. Many of the bars in the far right of the IRT/OP functions (bottom panels) axe cut off. X-axes: 0.01 s or 0.1 s bins (as indicated in axes labels); Y-axes: relative frequency or IRTS/OP (as indicated in axes labels).

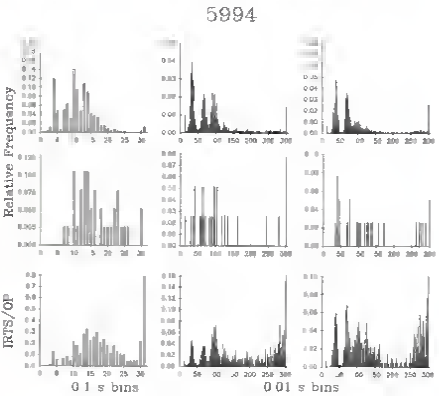

5994
Relative Frequency
IFTS/OP
0 1 s bins
0 01 s bins

Figure 1# Distribution of all IRTS, distribution of reinforced IRTS and IRT/OP functions for the last session under each of 3 baseline phases for Pigeon 2760. The distribution of all IRTS (top panels) and reinforced IRTS (middle panels) are expressed as proportions of the total. The bars representing the IRT/OP functions (bottom panels) for the last bin (>3.0 s) are cut off. X-axes: 0.1 s bins; Y-axes: relative frequency or IRTS/OP (as indicated in axes labels).

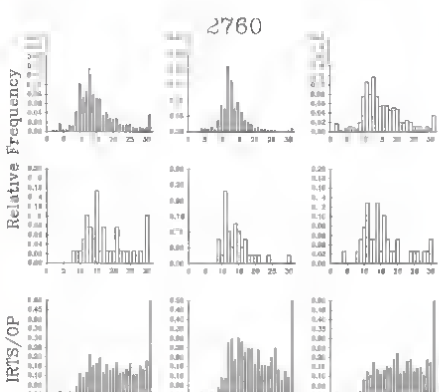

2760
Relative Frequency
IRTS/OP
0.1 s bins

Figure 19. Distribution of all IRTS, distribution of reinforced IRTS and IRT/OP functions for the last session under each of 3 experimental phases for Pigeon 1097. The distribution of all IRTS (top panels) and reinforced IRTS (middle panels) are expressed as proportions of the total. The particular experimental phase is indicated at the top of each column. Some of the bars in the far right of the IRT/OP functions (bottom panels) are cut off. X-axes: 0.01 s or 0.1 s bins (as indicated in axes labels); Y-axes: relative frequency or IRTS/OP (as indicated in axes labels).

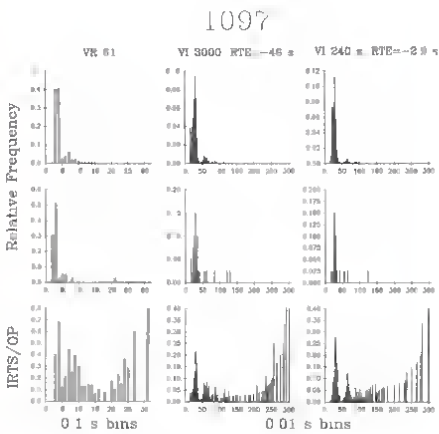

1097
VR 61
VI 3000 RTE=46 s
VI 240 s RTE=29 s
Relative Frequency
IRTS/OP
0 1 s bins
0 01 s bins

Figure 20. Distribution of all IRTs, distribution of reinforced IRTs and IRT/OP functions for the last session under each of 3 experimental phases for Pigeon 5594. The distribution of all IRTs (top panels) and reinforced IRTs (middle panels) are expressed as proportions of the total. The particular experimental phase is indicated at the top of each column. Some of the bars in the far right of the IRT/OP functions (bottom panels) are cut off. X-axes: 0.01 s or 0.1 s bins (as indicated in axes labels), Y-axes: relative frequency or IRTs/OP (as indicated in axes labels)

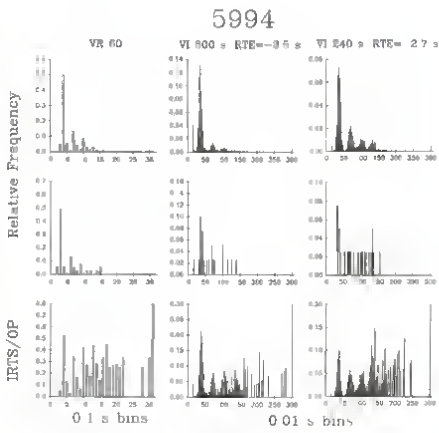
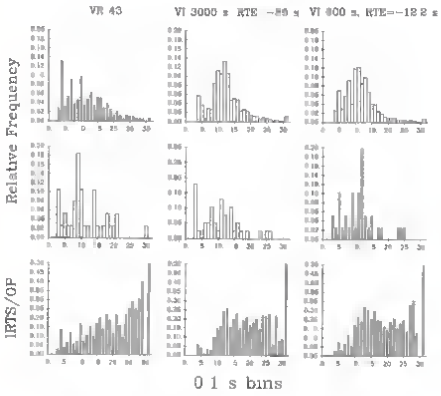

5994
VR 60
VI 500 s RTE=—3 5 s
VI 540 s RTE= 2 7 s
Relative Frequency
IRTS/OP
0 1 s bins
0 01 s bins

Figure 2i Distribution of all IRTS, distribution of reinforced IRTS and IRT/OP functions for the last session under each of 3 experimental phases for Pigeon 2750. The distribution of all IRTS (top panels) and reinforced IRTS (middle panels) are expressed as proportions of the total. The bars representing the IRT/OP functions (bottom panels) for the last bin (>1.0 s) are cut off. X-axes: 0.1 s bins; Y-axes: relative frequency or IRTS/OP (as indicated in axes labels).


2760
VR 43
VI 3000 s RTE = 86 s
VI 600 s, RTE=~122 s
Relative Frequency
IRTS/OP
0 1 s bins

very short IRTs--probably produced by opening and closing the beak--with the mode around 0.3 to 0.4 s. Recall, also, that where 0.01 s bins were used, IRTs less than 0.14 s could not be recorded.

The baseline IRT distributions for 1097 and 5994 (Figures 16 and 17, top panels) were quite similar. Distributions for both subjects were multimodal with modes around 0.3 to 0.4 s, 0.6 to 0.7 s, 0.8 to 1.0 s and 1.2 to 1.4 s. This suggests that when the pigeons are actually engaged in "pecking the key" their heads are moving with a fairly constant rhythm and that only a portion of these head motions result in closure of the microswitch. The IRT distributions for 1097, however, differ from those for 5994 in that there is a frequently a prominent mode at about 1.7-1.9 s for 1097. Pigeon 5994, on the other hand, emitted some IRTs that were about 0.14 s in duration. The IRT distributions for Pigeon 2760 under baseline conditions were quite different than those for Pigeons 1097 and 5994. The most prominent feature of this pigeon's data was the mode at about 1.2-1.4 s. (Recall that these distributions should be shifted about 0.05 s to the left because of the data collection error.) There does, however, appear to be a second, smaller, mode at about 1.0 s. There is little indication, however, of the regularities present in the distributions of 1097 and 5994. It is possible, however, that this pigeon's distribution reflects poor "accuracy" and

that it is actually responding at the dominant rhythm but closes the microswitch only after 3 or 4 "misses."

Comparing the top panels of Figures 16, 17, and 18 with those of 19, 20, and 21 reveals that for all 3 subjects changing the schedule to interlock or ratio increased the proportion of IRTs falling in the mode which occurred at about 0.4 s and decreased the proportion of IRTs in the bins which were integral multiples of this mode as well as IRTs which were apparently unrelated to this rhythm. For Pigeons 5994 and 1097 the distributions became nearly unimodal with by far the largest proportion of IRTs falling in the mode representing the dominant rhythm and the rest being in bins that are roughly integral multiples thereof. Both Pigeons 1097 and 5994 did, however, show some very short IRTs. For Pigeon 5994 these IRTs were clearly distinguishable from those at about 0.3 to 0.4 s but, for Pigeon 1097, very short IRTs and those at about 0.3 to 0.4 s tended to "blend" into one mode. Pigeon 2760's IRT distributions remained very similar to those observed under baseline conditions with the largest mode still typically between 1-2 and 1-5 s. There was, however, some indication that the same rhythm that characterized the responding of 1097 and 5994 (0.3 to 0.4 s) emerged during the experimental phases for Pigeon 2760. This is especially clear in the data for this Pigeon from VR 43 (Top left panel) and also from VI 600 s, RTE=-12.2 s.

The distribution of reinforced IRTs closely resembled the distribution of all IRTs under the interlocking and

ratio schedules, especially for Pigeons 1097 and 5994. Under VI, however, the relationship between the distribution of reinforced IRTs and that of all IRTs was somewhat more complicated. In general, however, there were fewer short IRTs, and more long IRTs reinforced than would be expected simply on the basis of the IRT distribution.

The IRT/OF functions (3rd row) for both VI and interlock/VR schedules display the obvious regularity which characterizes the IRT distributions for Pigeons 1097 and 5994. That is, the peaks are, for the most part, located at about integral multiples of 0.3 to 0.4 s. There are, however, differences between these functions for VI compared to interlock/VR for these two pigeons. Under VI, the highest local mode was never the mode representing the dominant, fundamental pecking rhythm and the IRT/OF values associated with successive peaks (left to right) tended to increase reaching a peak around 1 or 1.5 s. Under interlock/VR schedules, however, the IRT/OF value associated with the dominant rhythm was typically greater than that associated with the peak at twice this. For Pigeon 1097 the mode at about 0.3 s was the highest and the IRT/OF values associated with successive peaks decreased over the next second. For 5994, there was still some slight increase across successive peaks after the second one.

The IRT/OF functions for 2760 were considerably different from those for Pigeons 1097 and 5994 in ways that parallel the differences in IRT distributions.

Figures 22, 23, and 24 show average IRT duration as a function of the ordinal position (post-reinforcement) of the response that concludes the IRT for Pigeons 1087, 5894, and 2760, respectively. The point plotted above the x-axis value, 1, is the average post-reinforcement pause. The left-hand panels of Figures 22 and 23 show data from the last three sessions of VI before an experimental phase, and the right-hand panels show data from the last three sessions of that particular experimental phase. Data of this type are not available for 2760 under any of the experimental conditions that produced changes in behavior except under the condition in which the IRT value was a function of responding. Data are, therefore, presented only for VI for this pigeon. For all three pigeons, under VI, average IRT duration tended either to be shortest immediately after the post-reinforcement pause followed by slight increases over successive responses, or to decrease slightly over about 10-20 responses and to increase thereafter. Pigeons 5894 and 2760 showed both of these patterns while Pigeon 1087 tended to show only the latter. For Pigeons 1087 and 5894 interlock and ratio schedules increased post-reinforcement pauses relative to VI schedules and greatly decreased the average duration of IRTs. IRT duration remained virtually constant following the post-reinforcement pause under interlock/VR for 5894 but tended to increase very slightly for Pigeon 1087. Under VI average postreinforcement pause was typically between 1.5 (Pigeon 1087) and 2.0 s (Pigeons

Figure 22. Average IRT duration as a function of ordinal position post-reinforcement during the last 3 sessions under a representative experimental condition and its preceding baseline phase for Pigeon 1097. The first point in each panel is the average latency to the first response post-reinforcement. The condition is indicated at the top of each column. X-axes: ordinal position in interreinforcement interval; Y-axes: IRT duration in 0.01 s units.

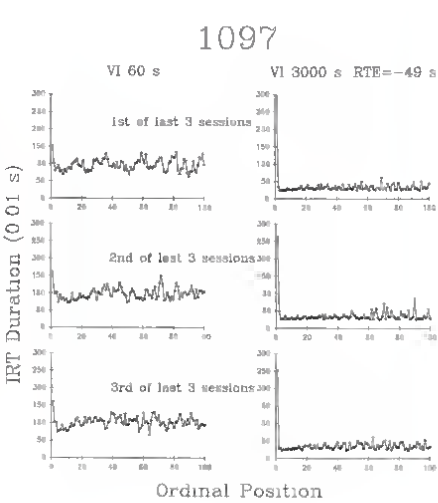

1097
VI 60 s
VI 3000 s RTE=−49 s
1st of last 3 sessions
2nd of last 3 sessions
3rd of last 3 sessions
IRT Duration (0.01 s)
Ordinal Position

Figure 23. Average IRT duration as a function of ordinal position post-reinforcement during the last 3 sessions under a representative experimental condition and its preceding baseline phase for Pigeon 5584. The first point in each panel is the average latency to the first response post-reinforcement. The condition is indicated at the top of each column. X-axes, ordinal position in interreinforcement interval; Y-axes: IRT duration in 0.01 s units.

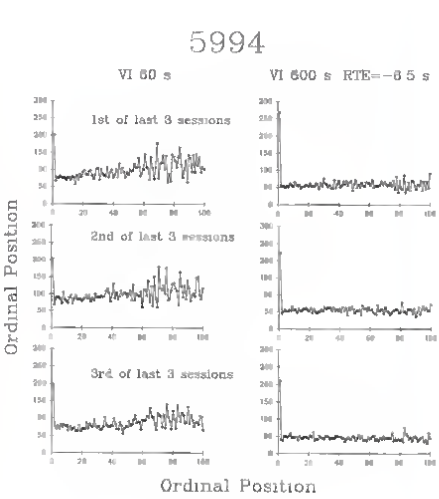
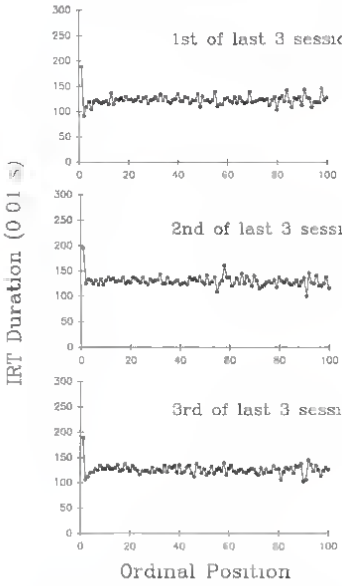

5994
VI 60 s
VI 600 s RTE=−6 5 s
1st of last 3 sessions
2nd of last 3 sessions
3rd of last 3 sessions
Ordinal Position
Ordinal Position

Figure 24. Average IRT duration as a function of ordinal position post-reinforcement during the last 3 sessions under a representative baseline phase for Pigeon 2760. The first point in each panel is the average latency to the first response post-reinforcement X-axes: ordinal position in interreinforcement interval; Y-axes: IRT duration in 0.01 s units

2760


VI 60 s
1st of last 3 sessions
2nd of last 3 sessions
3rd of last 3 sessions
IRT Duration (0.01 s)
Ordinal Position
300
250
200
150
100
50
0
0
20
40
60
80
100

5994 and 2760) for all three pigeons. Under interlock/VR average postreinforcement pause increased to between about 2.5 and 3.0 s for Pigeon 1097 and increased only slightly for Pigeon 5994.

Figures 25, 26, and 27 show IRT duration as a function of ordinal response position for Pigeons 1097, 5994, and 2760, respectively. The data are not averages but are, rather, from some single inter-reinforcement periods that contained at least 100 responses. The inter-reinforcement periods were all taken from the last session (bottom left and right panels of Figures 22, 23, and 24) of baseline and the last session of the succeeding experimental phase. Typically, there were not more than 3 or 4 reinforcers that were preceded by 100 or more responses. Given that there were more than 3, selection of the intervals for display was based on their location in the session. That is, intervals were chosen, where possible, when they were approximately 1/3 or 2/3 through the session, or near the end of the session. These data may be compared to the average IRT durations in Figures 22, 23, and 24 to provide some idea of the actual patterns that enter into the calculation of the mean. For Pigeons 5994 and 1097, the increase in average IRT with successive responses appeared to be due to the increasing probability of IRTS that did not reflect the dominant rhythm. There was also some tendency for the shortest class of IRTS reflecting the dominant rhythm to be most probable within the first 20 IRTS post reinforcement

Figure 25. IRT duration as a function of ordinal position post-reinforcement for some selected interreinforcement intervals which occurred during the last session under a representative experimental condition and its preceding baseline phase for Pigeon 1097. The first point in each panel is the latency to the first response post-reinforcement. The condition is indicated at the top of each column and the ordinal position of the interreinforcement interval is indicated in each panel. X-axes, ordinal position in interreinforcement interval; Y-axes; IRT duration in 0.01-s units.

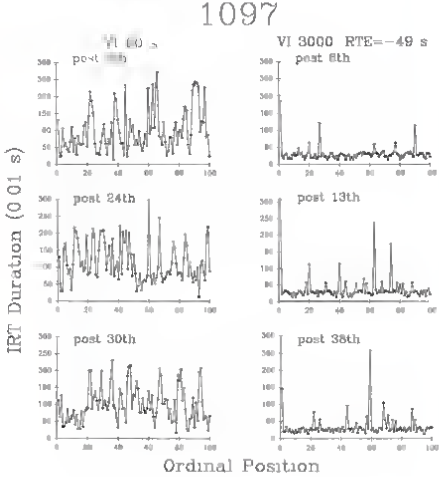

1097
VI 3000 RTE=-49 s
post 6th
post 24th
post 13th
post 30th
post 38th
IRT Duration (0.01 s)
Ordinal Position

Figure 26. IRT duration as a function of ordinal position post-reinforcement for some selected interreinforcement intervals which occurred during the last session under a representative experimental condition and its preceding baseline phase for Pigeon 5994. The first point in each panel is the latency to the first response post-reinforcement. The condition is indicated at the top of each column and the ordinal position of the interreinforcement interval is indicated in each panel. X-axes: ordinal position in interreinforcement interval; Y-axes: IRT duration in 0.01 s units.

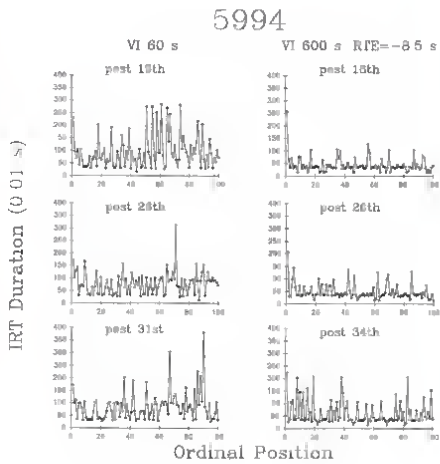
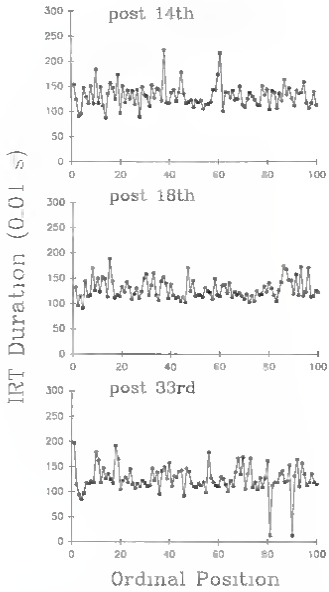

5994
VI 60 s
VI 600 s RTE=-8.5 s
post 19th
post 15th
post 25th
post 26th
post 31st
post 34th
IRT Duration (0.01 s)
Ordinal Position

Figure 27. IRT duration as a function of ordinal position post-reinforcement for some selected interreinforcement intervals which occurred during the last session under a representative baseline phase for Pigeon 2760. The first point in each panel is the latency to the first response post-reinforcement. The ordinal position of the interreinforcement interval is indicated in each panel. X-axes: ordinal position in interreinforcement interval; Y-axes: IRT duration in 0.01 s units.


2750
VI 60 s
post 14th
post 18th
post 33rd
IRT Duration (0.01 s)
Ordinal Position
0
50
100
150
200
250
300
0
20
40
60
80
100

For Pigeon 2760 the shortest IRTS also tended to be directly after the FRP. More than this cannot be said as it is not clear whether this pigeon's data reflect the same kind of rhythm as Pigeons 1097 and 5954, or some other rhythms entirely.

Figures 28, 29, and 30 show IRT duration as a function of ordinal response position in the session for Pigeons 1097, 5954, and 2760, respectively. The left-hand panels show data from the last 3 sessions of VI 60 s and the right-hand panels data from the last 3 sessions of the experimental phase which followed. For Pigeon 2760 no data of this kind exist for experimental phases within the 3-dimensional space, except for during the 50% schedule, and this schedule produced no changes in any dimension of responding.

For all 3 pigeons the temporal pattern of responding was not consistent over the whole duration of the session during baseline. For Pigeon 1097, there were periods during which there were relatively few IRTs in the first (lower) band of the dominant keypeck rhythm, but these periods were seldom present before 500 responses had occurred. During these periods there was a slight increase in the density of points in the region from about 1.4-2.1 s. For this pigeon, there was a slight tendency for the longest IRTS (i.e., those greater than about 2.0 s) to become less frequent as the session proceeded. Thus, for Pigeon 1097, the longest and shortest IRTS tended to occur with a somewhat higher

Figure 28. IRT duration as a function of ordinal position in the session during the last 3 sessions under a representative experimental condition and its preceding baseline phase for Pigeon 1097. The condition is indicated at the top of each column. X-axes: ordinal position in session; Y-axes: IRT duration in 0.01 s units.

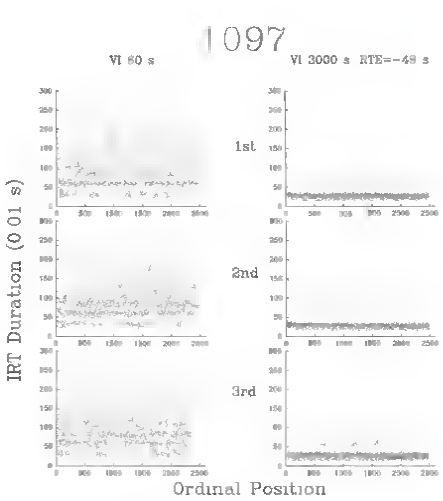

1097
VI 60 s
VI 3000 s RTE=-48 s
1st
2nd
3rd
IRT Duration (0 01 s)
Ordinal Position

Figure 29. IRT duration as a function of ordinal position in the session during the last 3 sessions under a representative experimental condition and its preceding baseline phase for Pigeon 5994. The condition is indicated at the top of each column. X-axes: ordinal position in session; Y-axes: IRT duration in 0.01 s units.

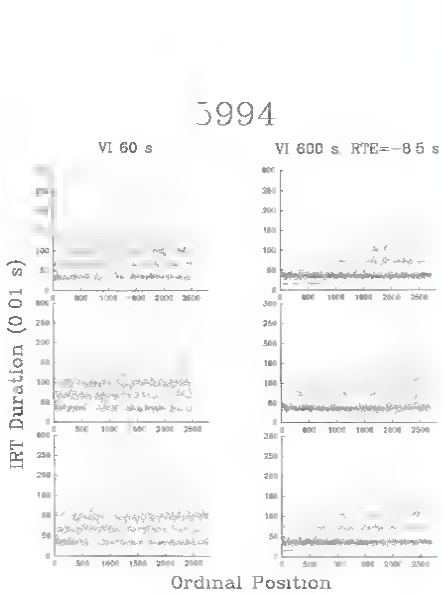
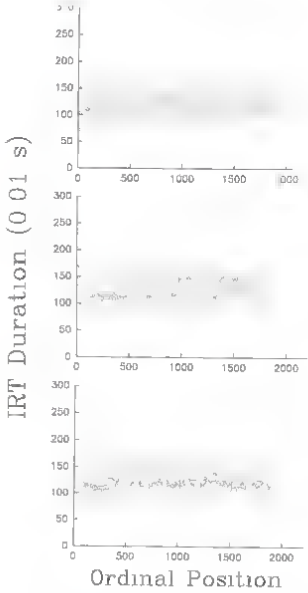

3994
VI 60 s
VI 600 s RTE=−8.5 s
IRT Duration (0.01 s)
Ordinal Position

Figure 30. IRT duration as a function of ordinal position in the session during the last 3 sessions under a representative baseline phase for Pigeon 2760. X-axes: ordinal position in session; Y-axes: IRT duration in 0.01 s units.

2760

VI 60 s


IRT Duration (0 01 s)
1st
2nd
3rd
0
50
100
150
200
250
300
500
1000
1500
2000
Ordinal Position

frequency at the beginning of the session. Pigeon 5994 displayed a similar type of fluctuation in responding across the session. Like Pigeon 1097, there were periods during which the "accuracy" was disrupted and during which IRTs not in the dominant rhythm occurred and these disruptions were unlikely within about the first 500 IRTs. Figure 30 offers some evidence that Pigeon 2760 did, in fact, exhibit the dominant rhythm but with low "accuracy." It is clear in this figure that there are modes at about 1.5 s and 1.2 s and a mode at about 0.9-1.0 s at the beginning of the session. This approximately 0.3 s difference in modes is consistent with the view that the fundamental rhythm is about 0.3 s. This would mean, however, that the pattern seen in Figure 26 could only be produced if the pigeon rarely closed the microswitch in the first three or 4 "pecks" following a preceding switch closure. Like Pigeons 1097 and 5994, Pigeon 2760's responding appeared slightly more "accurate" in the beginning of baseline sessions; the band located at about 0.9 s is slightly denser in all three sessions shown for about the first 500 responses.

In comparing the right-hand (interlocking schedules) to the left-hand panels a couple of features are apparent. For Pigeon 1797, all within-session changes essentially disappeared though there was some slight tendency for long IRTs to be absent from the beginning of the session. The band around 0.3 s became broader, now extending downward to 0.14 s. For Pigeon 5994, the within-session changes became

much more progressive. Bands representing 2 and 3 "misses" were essentially absent at the beginning of the session but emerged later, and in sequence--first "misses" of 2 emerging, then "misses" of 3. Sometimes even single "misses" were of low probability at the beginning of the session. The emergence of long IRTs not representing (apparently) the 0.3 s rhythm accompanied this progressive change in the probability of "misses." For Pigeon S994, too, very short (0.14 s) IRTs were present during the experimental phases.

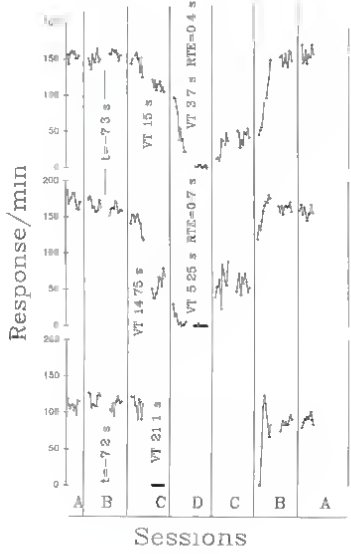
Experiment 2

Overall response rate

Figure 31 shows data from the first and last ten sessions of all phases of the experiment for all three pigeons beginning with the last ten sessions of the first condition. Phases are separated by vertical lines and the conditions are identified in the figure by letter and the condition associated with the letter is specified in the figure caption. This section will be primarily concerned with the steady- or stable-state data; that is, the last ten days of every phase.

Rate of response remained essentially unchanged for all 3 pigeons when the conditions were changed from VT 300 s, RTR=-15 s to VT 300 s, RTR=t (t=-7.3 s, -7.3 s, and -7.2 s for, respectively, Pigeons 1694, 1404, and 3673). Rate did decrease, however, when the causal relationship between responding and reinforcement was eliminated; that is, when

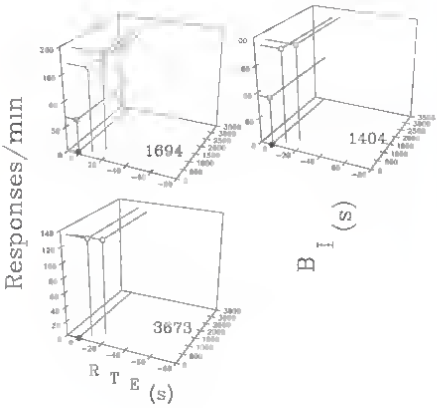
Figure 31. Overall session response rates during the first and last 10 sessions of most phases in Experiment 2. The particular phase is indicated by the letters at the bottom of the figure. The key is as follows: A:VT 600 s, RTE=-15-0 s; B: VT 300 s, RTE= t s (t is indicated in the figure); C: VT t s, RTE=0 s (the VT parameter is as indicated in the figure); D:VT t s, RTE=t' s (both t and t' are indicated in the figure). For the first "A" phase indicated, the last 10 sessions of the condition are shown. For the second "A" phase, the first ten sessions are shown. Sessions in which the data were lost, or the protocol compromised, are not shown. Y-axes: responses per minute.


Response/min
Sessions
A
B
C
D
C
B
A
t = 7 2 s
t = 7 3 s
VT 21 1 s
VT 14 75 s
VT 15 s
VT 5 25 s
RTE = 0 7 s
VT 3 7 s
RTE = 0 4 s
1694
1404
3673

the schedule was changed to VT (t=15.0 s, 14.75 s, and 21.1 s for, respectively, Pigeons 1694, 1404, and 3673). For Pigeon 1694 the change in overall rate of response produced by changing the schedule to VT was so slow (this condition was in effect for 55 sessions) that responding was not permitted to become steady or stable. For Pigeon 3673 responding was eventually eliminated following this change in conditions. For the two pigeons in which responding was not eliminated during VT, the schedule was changed to one in which responding added time to the currently scheduled interval. This manipulation reduced rate of response nearly to zero for these two pigeons. Reintroducing the VT 300 s, RTE=t s conditions resulted in increases in rate of response. For Pigeons 1694 and 1404 rate of response returned to its original level but for 3673 it stabilized at a level slightly lower than when the condition was previously in effect.

Figure 32 shows the maximum rate of response in each phase plotted as a function of BI and RTE. These data show what this experiment reveals about the shape of the surface formed when maximum rate of response is plotted as a function of BI and RTE. As in Experiment 1, the data indicate that simultaneously increasing BI and decreasing RTE results in large increases in maximum rate of response up to a point after which further changes in the contingencies no longer result in increases in maximum rates of response. There were maximum rates that were

Figure 32. Maximum response rate as a function of RI and RTE under each type of schedule in Experiment 2. Subject numbers are indicated in each panel. X-axes: RTE value in seconds; Y-axes: maximum rate of response (responses/min); Z-axes: RI value in seconds.


Responses/min
1694
1404
3673
B I (s)
R T E (s)

intermediate to the highest and lowest for Pigeons 1694 and 1404. These intermediate rates occurred under VT schedules. They were intermediate to the maximum rates produced by schedules with positive RTE values and those with negative RTE values.

Molecular description

Figure 33 shows IRT distributions from the last session of the original condition, VT 600 s, RTE=-15 s, for all three pigeons and Figure 34 shows data from the last session under VT for 1694 and 1404. Responding was eventually completely eliminated for Pigeon 3673 under VT. Each subject's data appear in a single column and the panels show, from top to bottom, the distribution of IRTs, the IRT/OP function, and the distribution of obtained delays. (i.e., the latencies from the last response which meets criteria to food presentation.)

Both Pigeons 1694 and 3673 showed a prominent mode in their IRT distributions (Figure 33 top panels) at about 0.35 s and a much smaller mode at about 0.65-0.70. Pigeons 1694 and 1404 were also similar in that both had the largest mode at about 0.14 s. 3673 had few such short IRTs and 1404 had few IRTs in the 0.3 to 0.4 s range, but more importantly, it is not clear that there is even a small mode for Pigeon 1404 in this range. This suggests that the rhythm displayed by most of the subjects in Experiment 1 and 2 with about 0.3 s as the fundamental was not displayed by this pigeon. It is possible that the variation around this higher frequency

Figure 31. IRT distributions, IRTS/OP, and the distribution of delays to reinforcement for the last session of VT 600 s, RTE=-15.0 s for all three pigeons in Experiment 2. The IRT distributions (top panels) are expressed as relative frequencies as are the distributions of delays (bottom panels). The IRT/OP functions appear in the middle (top to bottom) panels. Subject numbers appear above each column. X-axes: 0.01 s bins, Y-axes: relative frequency or IRTS/OP (as indicated by axes labels.)

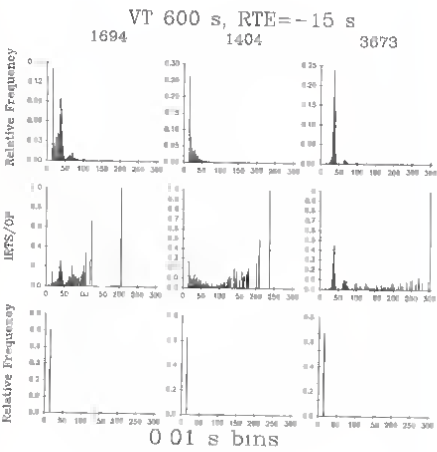
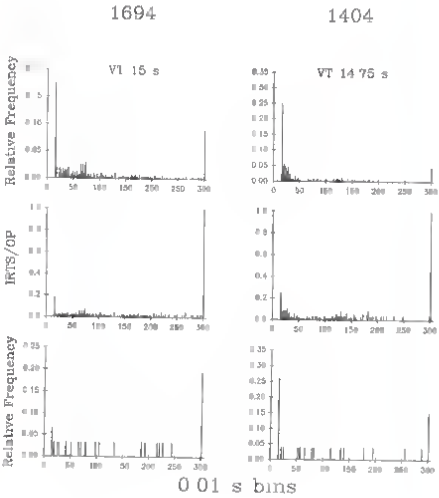

VT 600 s, RTE=-15 s
1694
1404
3673
Relative Frequency
IRTS/DF
Relative Frequency
0.01 s bins

Figure 34. IRT distributions, IRTS/OF, and the distribution of delays to reinforcement for the last session of VT t = for Pigeons 1694 and 1404. The IRT distributions (top panels) are expressed as relative frequencies as are the distributions of delays (bottom panels). The IRT/OF functions appear in the middle (top to bottom) panels. Subject numbers appear above each column. X-axes: 0 01 s bins; Y-axes: relative frequency or IRTS/OF (as indicated by axes labels.)


1694
1404
VI 15 s
VT 14 75 s
Relative Frequency
IRTS/OP
Relative Frequency
0 01 s bins

rhythm (around 0.14 s) is large enough to obscure a small mode at the typical dominant rhythm.

The IRT/OF functions (middle panels) for 1694 and 3673 reveal the way the 0.3 to 0.4 s rhythm observed in both experiments (except for Pigeon 1404) translates into temporally local probability of response. For both Pigeons there are local maximums in the functions at about 0.35 s, 0.7 s, 1.0 s, and 1.3 s as could be predicted from the IRT distributions. The local probabilities, however, are not necessarily obvious from looking at the IRT distributions. For Pigeon 1694 the most prominent mode in the IRT distribution was at about 0.14 s. This corresponded to a peak in the IRT/OF function but not necessarily the highest peak. For 1404 it is difficult to see from the IRT distribution that a keypeck was very unlikely at about 0.5 s from the preceding peck, but was rather likely at about 1.25 s.

As can be seen from the bottom panels of Figure 33, the delay to reinforcement was always the minimum possible (0.14 s) given the programming time required to implement the contingencies and collect data. This arose because the temporal locus of each response was collected and this value had to be allocated to its proper position in a 2-dimensional array.

The IRT distribution (Figure 34, top left panel; no data appear for Pigeon 3673 as responding was eliminated under this condition) for Pigeon 1694 was quite different

under VT from what it was under VT 600 s, RTE=-15 s (Figure 33, top left panel). While the mode at 0.14 s is still prominent, the mode at 0.3 to 0.4 s is essentially gone as is the one at 0.6 to 0.7 s. In addition there were many more IRTs that were longer than 3.0 s. The IRT distribution for 1404 showed a similar change in long IRTs but for this pigeon the rest of the distribution remained quite similar to that under VT 600 s, RTE=-15 s. For both Pigeons 1694 and 1404 the relative frequency of very short IRTs (<0.2 s) did not change much.

The IRT/OF function under VT for Pigeon 1694 showed little local structure, unlike that under VT 600 s, RTE=-15 s. Following the peak which corresponded to the short IRTs (0.14 s) the function was relatively flat up to about 0.6-0.7 s where the function had a local maximum. For 1404 the IRT/OF function remained quite similar to what it was under VT 600 s, RTE=-14.75 s.

Under VT there were frequently long delays between responses and food delivery. For Pigeon 1694 there were still a few "immediate" reinforcers but about 20-25% of the reinforcers were delayed more than 3 s with respect to criterion responses. (Noncriterion responses can always precede reinforcement and go unmeasured.) For Pigeon 1404 about 25% of the reinforcers were as immediate as possible under these arrangements (0.14 s) and around 20% were delayed more than 3 s.

Figure 35 shows average IRT as a function of ordinal position of the response post-reinforcement during VT 600 s, RTE=.15.0 s. The left, middle, and right columns show data from Pigeons 1654, 1404, and 3673, respectively. The top, middle, and bottom rows show, respectively, data from the first, second and third session of the last three sessions

For all three subjects average IRT duration remained rather constant for the first 99 responses post-reinforcement. There was, however, some tendency for the average IRT duration to show "spikes" at some distance from reinforcement. That is, there would occasionally be a position at which the average IRT duration was greater than the surrounding durations. These rarely occurred before the 20th response. IRT duration typically did not drop much below the level of the first 19 responses even where the durations became somewhat erratic from response to response because of the dwindling number of IRTS occurring at that distance from reinforcement. All 3 animals did, however, show large "spikes" of the type previously described at some distance from reinforcement. These could be discounted if the "spikes" in the opposite direction were as large, but they were not.

As can be seen in Figure 36, which shows cumulative responses, during VT, as a function of time since the start of the session for the two pigeons in which responding was not eliminated (Pigeons 1654 and 1404), responding was sometimes erratic within a session. This effect was

Figure 35. Average IRT duration as a function of ordinal position post-reinforcement during the last 3 sessions under VT 600 s, MTE = 15.0 s for all three pigeons in Experiment 2. The first point in each panel is the average latency to the first response post-reinforcement. The subject numbers are indicated at the top of each column. X-axes: ordinal position in interreinforcement interval; Y-axes: IRT duration in 0.01 s units.

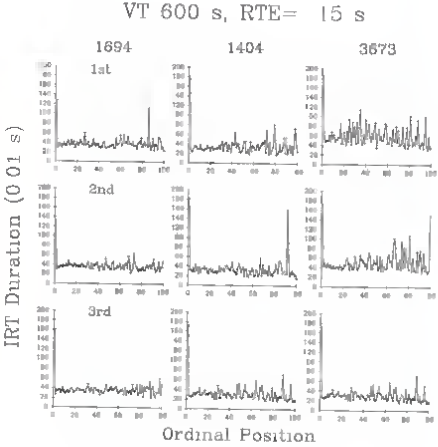
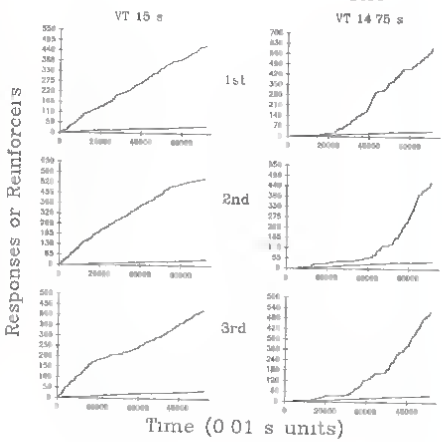

VT 600 s, RTE= 15 s
1694
1404
3673
1st
2nd
3rd
IRT Duration (0.01 s)
Ordinal Position

Figure 36. Cumulative number of responses and reinforcers as a function of time in session for Pigeons 1696 and 1404 during the last three sessions under VT t s. X-axes: time in session (0.01 s units); Y-axes: number of responses (top curve) or reinforcers (bottom curve).

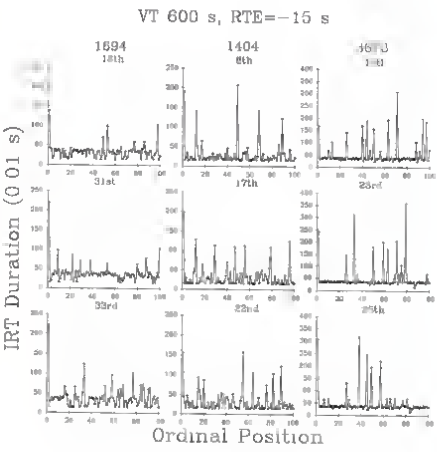

1694
VT 15 s
1404
VT 14 75 s
1st
2nd
3rd
Responses or Reinforcers
Time (0 01 s units)

extremely pronounced for Pigeon 1404 which responded at very low rates for the first third to half of the session. The line at the bottom of each panel shows cumulative food deliveries. Ties during which each reinforcer was present (3.0 s) was not removed from the data.

In order to appreciate the meaning of the average IRT durations shown in Figure 35, they may be compared with some nonaveraged data. Figure 37 shows such data taken from the last session (Bottom panels Figure 35.) of VT 600 s, RTS=.15 s. Each pigeon's data appear in a column and each panel in a column shows the latency to the first response postreinforcement and the succeeding 99 IRTS. These figures provide roughly the same kind of information that is provided by the IRT distributions with the exception that systematic changes in the distribution as a function of ordinal position postreinforcement may be revealed without actually producing distributions at each ordinal position.

Although the average IRT function does not show many "spikes" before about 20 responses, Figure 37 shows that relatively long IRTS did, indeed, occur within this range. For Pigeons 1654 and 1404 long IRTS appeared to be nearly equiprobable across ordinal position--at least judging from the 3 long intervals examined here. They must, however, be slightly more probable as the average functions show "spikes" for these pigeons at considerable distance from reinforcement. Not only may long IRTS in the same class interval increase in probability but longer and longer IRTS

Figure 37 IRT duration as a function of ordinal position post-reinforcement during selected interreinforcement intervals under VT 600 s, RTE=-15.0 s for all three pigeons in Experiment 2. The first point in each panel is the latency to the first response post-reinforcement. The subject numbers are indicated at the top of each column and the ordinal position of the interreinforcement interval is shown in each panel. X-axes: ordinal position in interreinforcement interval; Y-axes: IRT duration in 0.01 s units.


VT 600 s, RTE=−15 s
IRT Duration (0.01 s)
Ordinal Position

may become more probable. Such seems to be the case for 1404 given the very large average durations observable and the comparably long IRTS observed in the nonaveraged data. For Pigeon 3673 the probability of long IRTS clearly increased across ordinal position. In the 3 long intervals selected, the longest IRTS appear well after 20 responses.

Figure 38 shows IRT duration as a function of ordinal position in the session for the last 3 sessions of VT 600 s, RTE=.15.0 s. The maximum duration shown is 3 s. IRTS longer than this were rare or nonexistent. Not shown are the latencies between food presentations and the first response of an interreinforcement interval.

For all 3 subjects the overall molecular structure of responding was fairly constant over the whole session. That is, the IRT distributions shown in the top panels of Figure 33 may be taken as mostly indicative of the structure of responding throughout the session. For both 1694 and 3673, though, there was some tendency for longer IRTS to occur later in the session.

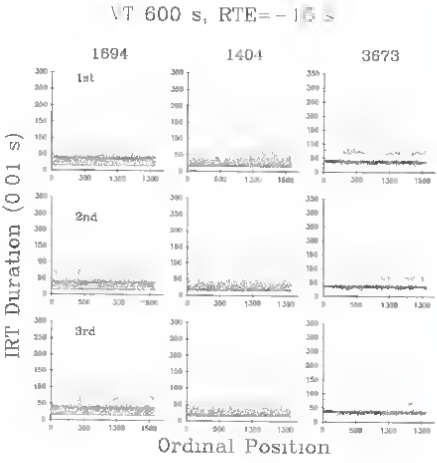
Transitions

Experiment 1

Overall response rates: VI-VR or interlocking

The first part of this section will be concerned with the transitions that occurred after transitions themselves seemed to have reached a steady state. For both Pigeons 5994 and 1097 the first or the first few transitions were

Figure 38 IRT duration as a function of ordinal position in the session during the last 3 sessions under VT 600 s, RTE=-15 0 s for all three pigeons in Experiment 2. The subject numbers are indicated at the top of each column. X-axes: ordinal position in session, Y-axes: IRT duration in 0.01 s units.


VT 600 s, RTE=-15 s
1694
1404
3673
1st
2nd
3rd
IRT Duration (0.01 s)
Ordinal Position

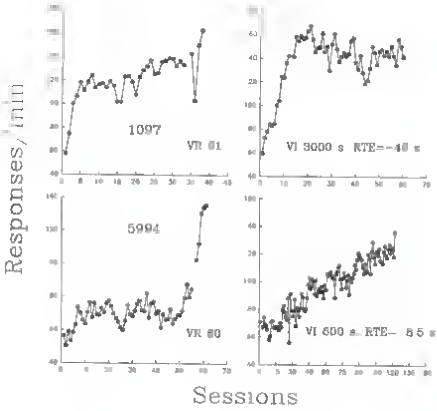
different than later transitions. These differences will be examined later.

Figure 12 shows only data from after the point at which transitions all had the same character within subjects. For Pigeon 1097, 4 experimental phases had occurred and for Pigeon 5994, 3 experimental phases had occurred. As can be seen from Figure 12, in Experiment 1 only Pigeon 1097 showed large increases in response rate during the first 10 sessions. Pigeon 5994 did, however, show small but fairly reliable increases in the first ten sessions.

Figure 39 shows two transitions for Pigeons 1097 and 5994. Two transitions are shown for Pigeons 1097 and 5994 in order to portray the range of what was observed. No panels appear for Pigeon 2760 in this figure as two entire experimental phases were depicted in Figure 15. This is because it is not clear that the response-rate changes that occurred for this pigeon represent a transition state rather than a transitory state. For Pigeon 1097 the data shown in the top left panel and where the data in the top left-hand panel of Figure 15 begin. For Pigeon 5994, both panels of Figure 39 end where the panels in Figure 15 begin. In the left hand panel for this pigeon, however, there is an overlap of seven sessions.

After the first 4 transitions from baseline to experimental conditions, Pigeon 1097 always showed rather dramatic increases in rate of response near the beginning of experimental phases. Following this increase during VR 60

Figure 35. Overall response rate as a function of sessions following the change from baseline to experimental phase during two different transitions for Pigeons 1097 (top panel) and 5994 (bottom panels). The particular experimental phase is indicated in each panel. Each transition followed exposure to VI 60 s. Sessions for which data were lost or protocol compromised are not shown, and some points are, thus, not connected. Note that the scales may differ. X-axes: sessions following phase change; Y-axes: responses per minute.


Responses/min
1097
VR 81
VI 3000 s RTE=-48 s
5994
VR 80
VI 600 s RTE= 8 5 s
Sessions

(Figure 39, top left) there was a more gradual increase for a period of approximately 35 sessions. During subsequent transitions, such as the one shown in Figure 39 (top right), rate of response typically increased rapidly to near the maximum.

Pigeon 5994 showed a rapid increase in rate of response in one transition (Figure 39, bottom left) but only after a period of relative stasis lasting nearly 50 sessions. At the beginning of this transition, however, there was a rather rapid, but modest, increase in rate of response which preceded the period of stasis. In this sense, there is actually a strong resemblance between the two left-hand panels of Figure 39. For Pigeon 1097, too, there was a period of relative stasis. It is clear that 1097 did not show such a dramatic increase in rate of response following this period of stasis, but it is not clear that it cannot be characterized as "periods of stasis followed by periods of response-rate increases." A similar description may be suggested for the steady-state oscillations; the system is cycling between 2 or 3 nonstable states. Despite the conceptual nature of the issues raised, this topic is introduced in the Results section because there is a purely descriptive aspect to it. Here the question is, 'How reasonable is it to characterize the data as 'periods of relative stasis punctuated by response rate changes?'" It was rare for Pigeon 5994 to show increases in rate of response as dramatic as the one shown in the bottom left of

Figure 39. This pigeon's other transitions more resembled that in the bottom right-hand panel. Even here, though, it is not clear that the increased rate should be seen as steady. Even with the x-axis compressed in this panel, there appear to be 3 or 4 periods of relative stasis.

For Pigeon 2760 (Figure 15) changing to an experimental phase produced a period of time (about 50 sessions) during which rate of response increased slowly. This was then followed by a decline in response rate to baseline levels. These phases were, unfortunately, not carried on long enough to say if rate of response would have increased again to levels comparable to those observed at about 50 sessions after the phase-change. It could be argued that Pigeon 2760's data resemble those of the other two pigeons in terms of alternate stasis and acceleration; in the case of this pigeon the steady-state performance maintained under the VI 60-s schedule may be an unstable-state under interlocking conditions. Indeed, this action is implicit in including the transition in with the steady-state data for Pigeon 2760 in Figure 15. For the other two pigeons a transition state was easily identified, in retrospect, after the phase was run long enough to ascertain the range of oscillations during the "steady-state." For Pigeon 2760, that range of oscillation included the baseline rates of response. Similarly, for Pigeon 5994, the very large increase shown in the bottom left-hand panel of Figure 39 is also shown in the middle left-hand panel of Figure 15 which shows steady-state

data. This is because the range of variation in the steady-state encompasses the unstable steady-state away from which response rate accelerated. On the other hand, however, it seemed unreasonable to exclude this aspect of the data from the section on "transitions" since the increase occurred in the context of a more general, long-lasting increase (containing, albeit, a rather long period of stasis).

Molecular data: VI to VR or interlocking

Figures 40, 41, and 42 show the IRT distributions for all three subjects at various points during one transition. (The conditions for Pigeons 1897, 5994, and 2760 were, respectively, BI=3000 s with RTE=-49 s, BI=600 s with RTE=-8.5 s, and BI=600 s with RTE=-12.2 s.) Each panel is labeled as to the ordinal position of the session which it depicts. The sessions were selected so as to cover, in cross section, the portion of the experimental phase when response rate was increasing. These figures may be compared to the final distributions which appear in Figures 16 through 21.

For all three subjects, there were two general changes in response patterning; the subjects responded more at the 0.3- to 0.4-s rhythm and more "accurately" while doing so. Here "accuracy" is defined in terms of the relation between the mode occurring at about 0.3 to 0.4 s and its integral multiples. The higher the relative frequency of IRTs in the fundamental mode, the better the "accuracy." There was little evidence that these two different kinds of

Figure 40. Relative frequency of different IRTS for the first 5 sessions following the change from baseline to a representative experimental phase (VI 3000 s, RTI=-49.0 s) for Pigeon 1097 X-axes: 0.01 s bins; Y-axes: relative frequency

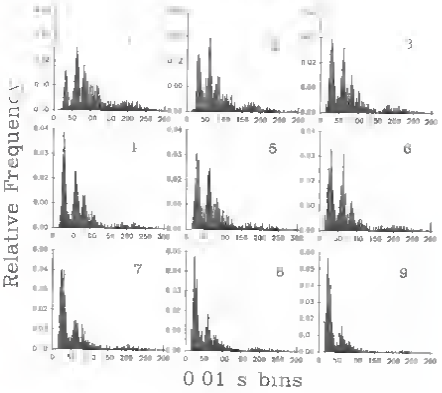

Relative Frequency
0 01 s bins

Figure 41. Relative frequency of different IRTs for selected sessions following the change from baseline to a representative experimental phase (VI 600 s, RTE=-8 s) for Pigeon 5394. The ordinal position of the session is given in each panel. X-axes: 0.01 s bins; Y-axes: relative frequency.

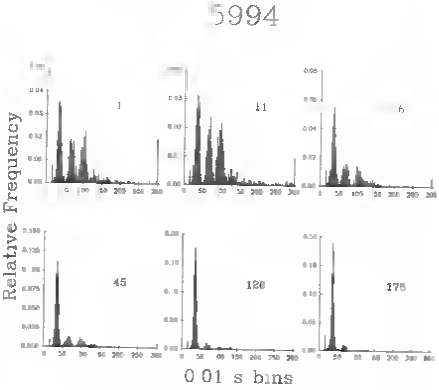
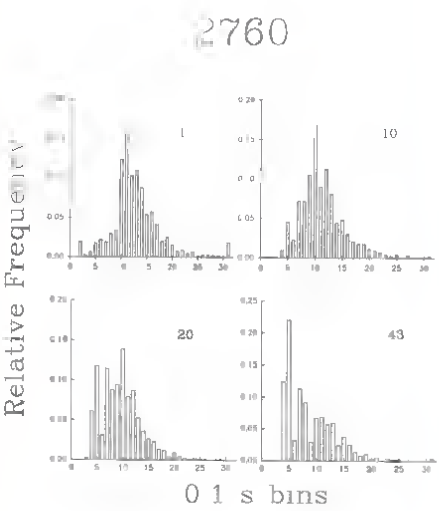

5994
Relative Frequency
1
11
6
45
120
175
0 01 s bins

Figure 42 — Relative frequency of different IRTS for selected sessions following the change from baseline to a representative experimental phase (VI 600 s, RTE=-12.2 s) for Pigeon 2760. The ordinal position of the session is given in each panel. X-axes: 0.1 s bins; Y-axes: relative frequency


2760
Relative Frequency
1
10
20
43
0 1 s bins

changes occurred at different times or different rates. By the third session after the phase change for 1097, the broad mode centered around 2.0 s was considerably reduced. That is, the pigeon was responding more at the 0.3 to 0.4 s rhythm. The relative frequency of IRTS representing the fundamental frequency (approximately 0.3 s) was also increased by the third or fourth session. This state of affairs seems to have continued through the transition. The case was similar with Pigeon 5994. Between Session 20 and Session 26 (Figure 41, top right) IRTS obviously unrepresentative of the 0.3 to 0.4 s rhythm decreased dramatically and the relative frequency of IRTS in the 0.3 s bin increased while relative frequency of "missed" decreased. For 2760, too, "accuracy" seemed to change along with the elimination of responding not related to the 0.3 to 0.4 s rhythm, but it is difficult to tell with this pigeon exactly what proportion of IRTS are unrelated to the 0.3 to 0.4 s rhythm.

Figures 43 and 44 show IRT duration as a function of the ordinal position in the session for Pigeons 1097 and 5994, respectively. Sessions were selected so as to cover the entire transition, and pairs of consecutive sessions are shown. The purpose of this analysis is mainly to ascertain the extent to which the changes in responding during the transition occurred within sessions. In adjacent sessions, the right hand panel always shows data from the session with the higher rate of response. The data in these figures may

Figure 43. IRT duration as a function of ordinal position in the session for selected sessions during the transition from baseline to a representative experimental phase (VI 3000 s, RTE=-49.0 s) for Pigeon 1097. The ordinal position of the session is given in each panel. X-axes: ordinal position in the session; Y-axes: IRT duration in 0.01 s units.

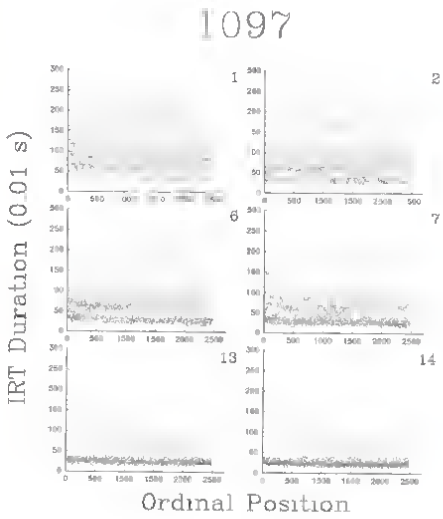
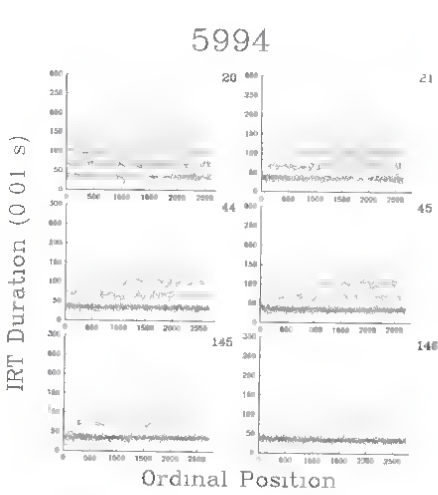

1097
1
2
6
7
13
14
IRT Duration (0.01 s)
Ordinal Position

Figure 44 IRT duration as a function of ordinal position in the session for selected sessions during the transition from baseline to a representative experimental phase (VI 600 s, RTE=-0.5 s) for Pigeon 5594. The ordinal position of the session is given in each panel. X-axes: ordinal position in the session; Y-axes: IRT duration in 0.01 s units


5994
IRT Duration (0 01 s)
Ordinal Position
20
21
44
45
145
146

be compared to those in Figures 29 and 29 which show this kind of analysis for the stable-state conditions which precede and succeed the transition.

For Pigeon 1097, there was some indication that there were within session changes in responding unlike, or more dramatic than, those that characterized the steady-state responding. In the two middle panels (sessions 6 and 7) the band at about 0.3 s became noticeably denser toward the end of session 6 and this seemed to carry thorough to the next session. Although there was a tendency for longer IRTS to become progressively rare under VI 60 s--a feature which can also be observed during the transition--there was little tendency for IRTS of about 0.3 s to become noticeably more probable within a session. This feature was not present in the other sessions between which there was a rate increase. Thus, for this pigeon, there was little indication that the changes within-sessions were nearly so large as those between sessions.

For Pigeon 5994, too, there was little indication of within session changes that were large enough to 'explain' the changes which occurred across-sessions. That is, the amount of change which occurred between sessions was very much greater than that which occurred within a session and the change that did occur within a session was comparable to that which occurred under steady-state conditions.

Overall Response Rate: Return to Baseline

As can be seen in Figure 12, all 3 subjects displayed a relatively rapid decrease in response rate when the schedule was changed back to VI 60 s, particularly within the first 2-5 sessions. Figure 45 shows a complete transition for each subject. For Pigeons 1097 and 5994 the data depicted are from the transition back to VI which followed the phase depicted in Figures 43 and 44. For Pigeon 2760 the transition followed the only schedule that reliably increased response rates--BI=6000 s, RTE= -26 s -4.0 s per response. For all 3 subjects response rates returned to baseline levels by about the 30th session. For 2760 rate of response increased on the first session following the change back to VI 60 s. For Pigeon 1097 the transition following change back to VI depicted in Figure 45 is not wholly representative of all of its transitions. The first portion of the transition was always the same for this pigeon, i.e., a rapid decrease within the first 10 sessions or so. During subsequent returns to the VI 60 s, however, this pigeon showed a wide fluctuation in response rates for up to approximately the first 40 sessions. This occurred despite the fact that, as in this instance, rate of response reached baseline levels within the first several sessions but did not remain there. The difference in rates of response between adjacent sessions could be dramatic--as much as nearly 40 responses per minute. Figure 46 shows one of

Figure 45. Overall response rate as a function of sessions following the return to baseline from an experimental phase for all 3 pigeons in Experiment 1. The experimental phases from which the schedule was changed were, respectively, for Pigeons 1097, 5994, and 2960: VI 3000 s, RTE=-43.0 s; VI 600 s, RTE=-8.5 s; and VI 6000 s, RTE=-26.0 - 4.0 s/response. Sessions for which data were lost or protocol compromised are not shown, and some points are, thus, not connected. X-axes: sessions following schedule change; Y-axes: responses per minute.

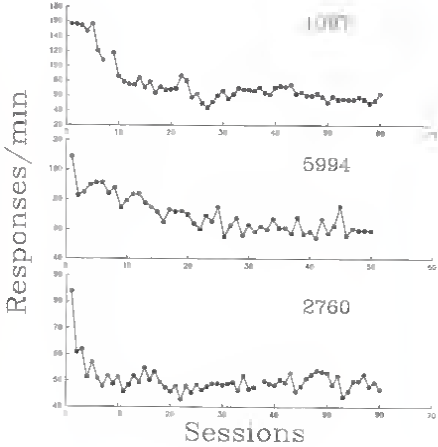
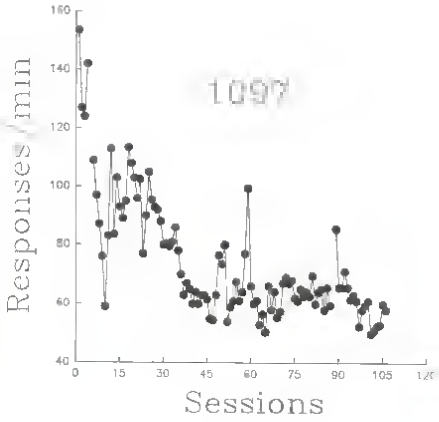

Responses/min
5994
2760
Sessions

Figure 45 Overall response rate as a function of sessions following the return to baseline from VI 240 s, ATE=-2.4 s for Pigeon 1097. Sessions for which data were lost or protocol compromised are not shown, and some points are, thus, not connected. X-axis: sessions following schedule change; Y-axis: responses per minute.


160
140
120
100
80
60
40
Responses/min
1097
0
15
30
45
60
75
90
105
120
Sessions

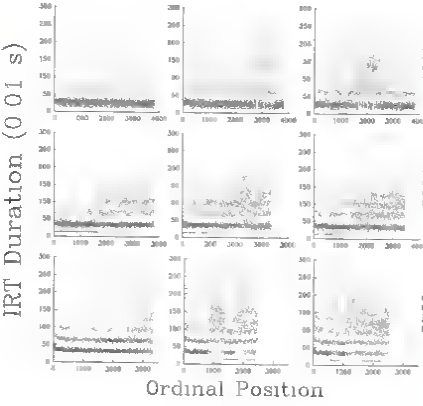
these transitions precipitated by the return to VI 60 s and should be compared to the top panel of Figure 45.

Molecular Description: Return to Baseline

Figure 47 shows IRT duration as a function of ordinal position for all 3 pigeons. Three consecutive sessions are shown for each subject. The sessions are taken from the beginning of the transition back to VI (Pigeons 5994 and 2760) or from very near the beginning (Pigeon 1057). The sessions were selected from the portion of the transition in which rate of response declined most dramatically. Due to programming limitations, only the first 3923 IRTS were recorded. Typically this limitation was not exceeded. The exception occurred when the schedule was changed back to VI 60 s. Under these circumstances many more responses could be emitted than could be recorded (but response rates for these sessions were calculated for the entire session). For Pigeon 1057, in the 3 sessions shown, the number of responses were, 6377, 4894, and 4385. For Pigeon 5994, the first session shown was effected--there were 4445 responses in this session.

For Pigeon 1057 the pattern of responding during the recorded portion (see above paragraph) was similar to that seen during the steady-state produced in the experimental phases (Figure 25, right panels) except for two things: there were more longer IRTS throughout the session, and the general orderliness of responding was more punctuated than even under stable-state VI (Figure 25, left panels). As is

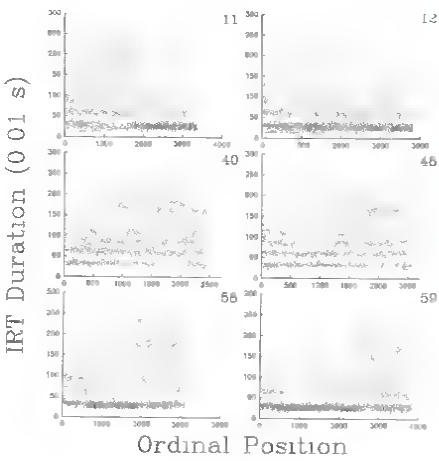
Figure 47. IRT duration as a function of ordinal position in the session for three consecutive sessions during the transition back to baseline for all three Pigeons in Experiment 1. For Pigeons 5994 and 2760 the first 3 sessions are shown and for Pigeon 1097 sessions 5, 6 and 7 are shown. The sessions shown were from the same transition depicted in Figure 42 (i.e., for Pigeons 1097, 5994, and 2760 the transitions were to VI 60 s from, respectively, VI 3000, RTE=.49.0 s; VI 600 s, RTE=.8.5 s; and VI 6000 s, RTE=.25.0 - 4.0 s/response). X-axes: ordinal position in session; Y-axes: IRT duration in 0.01 s units.


IRT Duration (0.01 s)
Ordinal Position
1097
5994
2760

apparent from the two upper right hand panels, there were brief periods of time during which there were virtually no IRTS in the band representing the fundamental rhythm. These graphs are thus similar to those in the top panels of Figure 28 in the sense that both contain two distinct patterns, the shifts between which occur quite abruptly. For Pigeon 5994, such dramatic shifts in the patterning were not apparent during this early portion of the decline in overall rate. Instead, as always for this subject, the probability of long IRTS increased across the session. The increase in probability of long IRTS across the session was similar to that observed under steady-state conditions (but which was especially apparent and gradual during experimental conditions). During the abrupt drop in rate of response depicted in the three sessions shown "misses" became more probable and very long IRTS--clearly not part of the 0.3 to 0.4 s rhythm--began to appear late in the session. For Pigeon 2760, the pattern of responding during the steep decline in rate of response was similar to the one observed for Pigeon 1097. That is, the sessions were comprised of two rather distinct patterns of responding that could appear and disappear quite abruptly. Also, like Pigeon 1097, the patterning which came to predominate during VI appeared earlier in a session and was longer-lived.

Figure 48 shows IRT duration as a function of ordinal position in the session for sessions during the transition back to VI 60 s which was depicted in Figure 46 (Pigeon

Figure 48. IRT duration as a function of ordinal position in the session for some selected sessions during the transition depicted in Figure 43 for Pigeon 1097. The ordinal position of the session post-phase change is indicated in each panel. X-axes: ordinal position in the session; Y-axes: IRT duration in 0.01 s units.


1097
11
12
40
45
58
59
IRT Duration (0.01 s)
Ordinal Position

1097). The two middle panels show sessions from during an 11-session portion in which rates were at baseline levels. The remaining two right-hand panels are data from sessions in which response rate was much higher than baseline, and the remaining two left-hand panels show data from the sessions which immediately preceded the high rate sessions. The rate of response in the session depicted in the top left panel was intermediate to the rates maintained under baseline and experimental conditions. The rate of response in the session which preceded this one was at baseline level as was the rate of response for the session shown in the bottom left panel. As can be seen from the top two panels, increases in rate of response across sessions can, in part, reflect changes within a session. The rate of response in the session which preceded these two sessions (session 13) was at baseline levels as was approximately the first half of Session 11. After the first half of Session 11, however, the pattern of responding became abruptly quite like that observed during the experimental phases. This pattern continued through the entire next session (top right-hand panel). During the 11-session portion from which the two middle panels were selected the pattern of responding was the same as that under steady-state VI conditions. As the bottom two panels show, however, responding was not stable as the pattern of responding abruptly shifted to one resembling that under experimental conditions.

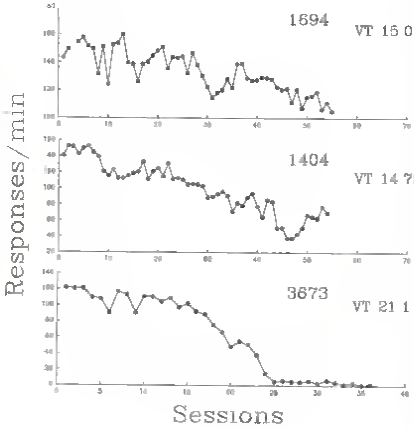
Experiment 2

Overall response rates: VT 300 s, RTE-t s to VT

As can be seen in Figure 31, rate of response declined only slightly, during the first ten sessions of VT, for all three pigeons considered here. Figure 49 shows rate of response as a function of sessions for each subject across all sessions of the phase. Session 1 is the first session following the change in schedule from VT 300 s, RTE-t s to the VT schedule.

During the 55 sessions in which this phase was in effect for Pigeon 1694, response rate declined only about 30-35% (note that the y-axis is truncated). The response rate for this pigeon was not allowed to become stable because of the extreme slowness of the change. Response rate did not change much during the first 25 sessions although there were occasional sessions with response rates lower than at any time during the stable portion of the preceding phase. After about the 25th session, response rate declined in a fairly steady, linear fashion. For Pigeon 1404 response rate was somewhat lower than during the stable portion of the preceding phase right at the beginning of the VT phase. Although some of these data points were barely outside of the range of those under the preceding phase, there was a clear effect; response rates were virtually never below 160 responses/min for more than 1 or 2 sessions under that phase. Following immediately upon the

Figure 49 Overall response rate as a function of sessions following the change from VT 300 s, RTE=t s to VT t s for all three pigeons in Experiment 2. The pigeon numbers are indicated in each panel. Sessions for which data were lost or protocol compromised are not shown, and some points are, thus, not connected. X-axes: sessions; Y-axes: responses per minute


1694
VT 15 0 s
1404
VT 14 75 s
3673
VT 21 1 s
Responses/min
Sessions

change to VT, response rates were between 140 and 153 responses/min for the first 5 sessions. Following this there was another abrupt drop in response rate, and for the next 12 sessions it stayed around 120 responses/min. This was followed by a rather slow steady decline until reaching the final state. For Pigeon 3673 the early portion of the transition resembled that of Pigeon 1694. That is, response rates remained, for the most part, at the level observed during the stable portion of the preceding phase. During this period there were a few sessions in which rate was slightly below the preceding level. After about the 13th session, however, response rate plummeted until reaching near zero levels at about the 25th session. Response rate declined slowly thereafter until responding ceased altogether.

Molecular Data: VT 300 a, RTE-t a to VT

Figures 50, 51, and 52 show IRT distributions at selected points during the transition from VT 300 a, RTE-t a to VT for, respectively, Pigeons 1694, 1404, and 3673. The sessions were selected, as before, to portray, in gross section, the entire transition. The ordinal position of the sessions portrayed are indicated in the figures.

For Pigeon 1694, there was little change in the IRT distribution during the 55 sessions in which the VT was in effect this first time. There is some indication, however, that "accuracy" of keypecking was slightly affected before

Figure 50 Relative frequency of different IRTS for selected sessions during the transition to VT for Pigeon 1f94. The ordinal position of the session is indicated in each panel X-axes: 0.01 s bins; Y-axes: relative frequency

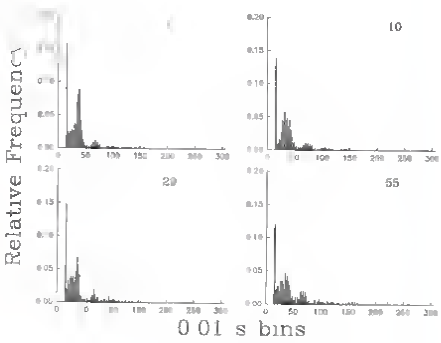

1694
Relative Frequency
10
20
55
0 01 s bins

Figure 5i. Relative frequency of different IRTS for selected sessions during the transition to VT for Pigeon 1404. The ordinal position of the session is indicated in each panel. X-axes: 0-01 s bins; Y-axes: relative frequency.

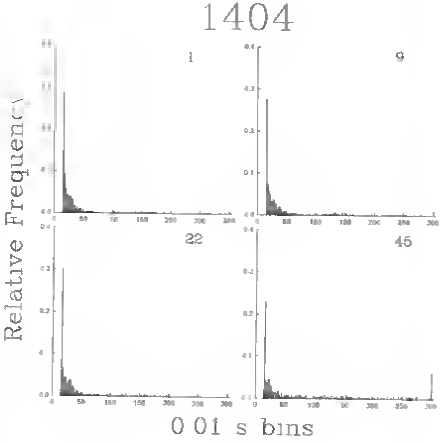
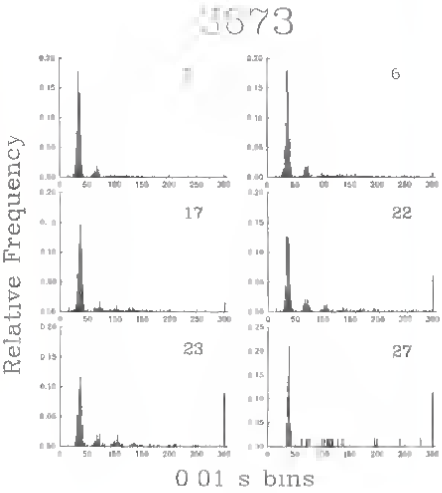

1404
1
9
22
45
Relative Frequency
0 01 s bins

Figure 52. Relative frequency of different IRTS for selected sessions during the transition to VT for Pigeon 3673. The ordinal position of the session is indicated in each panel. X-axes: 0-01 s bins; Y-axes: relative frequency.


573
6
17
22
23
27
Relative Frequency
0 01 s bins

the nonrhythmic responding appeared. In session 10, for example, the mode in the first bin representing the fundamental rhythm (about 0.3 s) was somewhat smaller than under the previous phase. The third mode representing the fundamental rhythm is somewhat larger and there is a cluster of IRTs at slightly less than 1.5 s showing, perhaps, the appearance of IRTs that are produced when the pigeon fails to close the switch for 3 successive "attempts" at a peck. These effects are, however, very small. This may be seen by comparing this panel with the one on the top left of Figure 50 (session 1) and also the top left one in Figure 33 (last session of VT 60" s, RTE=-15 s). By Session 55, the mode at about 0.3 s had clearly decreased and single misses had increased. There were also a few longer IRTs representing pecking that was not connected to the 0.3-s rhythm. There was little change in the relative frequency of the very short IRTs probably produced by opening and closing the beak. For Pigeon 1404, as was pointed out, it is difficult to distinguish between the two types of rhythmic responding. All that can be said is that nonrhythmic, long IRT responding increased in probability across sessions. For Pigeon 3673 it is clear that "accuracy" of keypecking and nonrhythmic responding changed together. This is especially clear in the data for Session 22 which contains modes produced by 2 and 3 misses as well as a great deal of nonrhythmic responding.

Figures 53, 54, and 55 show IRT duration as a function of ordinal position in the session for, respectively, Pigeons 1694, 1404, and 3673. The sessions shown are the same ones that are shown in Figures 50, 51, and 52. All panels within a figure are the same scale with the exception of the lower right-hand panel in Figure 55.

For all three subjects the within-session changes--or lack thereof--that prevailed under the earlier phases tended to persist during the transition to lower rates of response produced by the change to VT. This can be seen by comparing Figures 53, 54, and 55 with Figure 38. For Pigeons 1694 and 3673, IRT duration tended to increase across the session. This pattern was less pronounced and less reliable for Pigeon 3673 and was, perhaps, finally eliminated under VT.

During VT it was clear that for Pigeon 1694 the within-session changes involved both changes in "accuracy" and the probability of long "nonrhythmic IRTS." For this pigeon the "accuracy" degraded progressively across the session; first "single misses" appeared, and later "double misses" (i.e., at 2 and 3 times the base rhythm, respectively). This effect was somewhat more pronounced during the transition to VT than under the preceding stable-states. It was, to some extent, an exaggeration of the stable-state effect. The probability of double misses was greater later in the transition sessions than under the preceding stable-state, and the probability and length of the IRTS representing the

Figure 53. IRT duration as a function of ordinal position in the session for selected sessions during the transition to VT for Pigeon 1694. The ordinal position of the session is indicated in each panel. X-axes: ordinal position in the session; Y-axes: IRT duration.

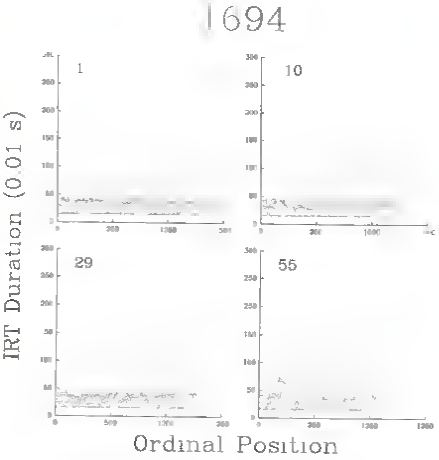

1694
1
10
29
55
IRT Duration (0.01 s)
Ordinal Position

Figure 54. IRT duration as a function of ordinal position in the session for selected sessions during the transition to VT for Pigeon 1404. The ordinal position of the session is indicated in each panel. X-axes: ordinal position in the session; Y-axes: IRT duration.

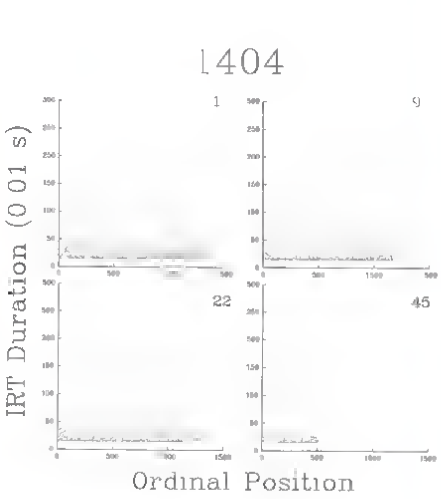
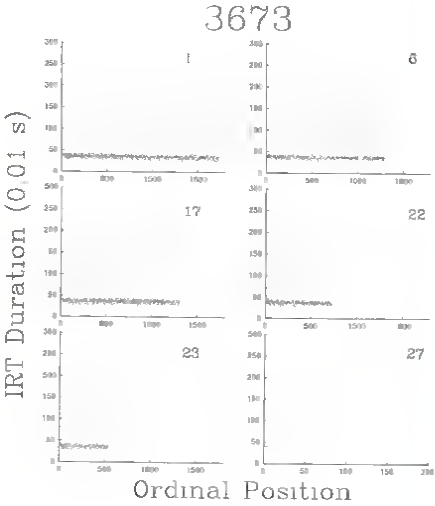

1404
1
9
22
45
IRT Duration (0 01 s)
Ordinal Position

Figure 55. IRT duration as a function of ordinal position in the session for selected sessions during the transition to VT for Pigeon 3673. The ordinal position of the session is indicated in each panel. X-axes: ordinal position in the session; Y-axes: IRT duration.


3673
1
6
17
22
23
27
IRT Duration (0.01 s)
Ordinal Position

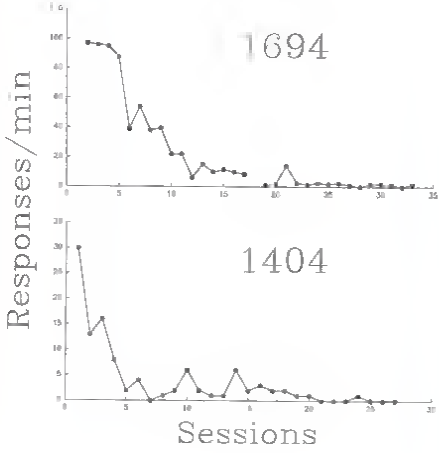
nonrhythmic responding were greater. For Pigeon 1404, there were no consistent within-session changes during the earlier phases and this state of affairs persisted during VT despite the overall downward trend in response rates.

Overall rate of response: VT to positive RTE values

Figure 56 shows the transition from VT to the phase in which responses added time to the currently scheduled interval for Pigeons 1694 and 1404. The parameter values used were, respectively, VT 3.7 s, RTE=0.4 s and 5.25 s, RTE=0.7 s. The change from VT to positive RTE values was one in which molar variables were held constant at the beginning of the change. For Pigeon 1694 data from the first session are not included because there was an apparatus failure on this day and no responses were reinforced and no food deliveries occurred. A second session was conducted on this day and response rate was very low. On the succeeding day response rates were almost as high as they were at the end of the preceding phase (about 100 responses per minute), so the transition was allowed to proceed.

In contrast to the slowness of the transitions to VT, the transitions to the phases with positive RTE values were quite rapid. For Pigeon 1694, responding was virtually eliminated by about the 21st session, and for 1404 by about the fifth session

Figure 56. Overall response rate as a function of sessions following the change from VT to the phase in which responses added time to the currently scheduled interval for Pigeons 1594 and 1404. X-axes: sessions following schedule change; Y-axes: responses per minute.


1694
1404
Responses/min
Sessions

Molecular descriptions: VT to positive RTE values

Figures 57 and 58 show selected IRT distributions for, respectively, Pigeons 1694 and 1404. For 1404 only the first session is shown as there were too few responses in subsequent sessions for the distributions to be very meaningful.

For Pigeon 1694, the IRT distribution did not change very much until the sixth session despite the fact that rate of response had declined to below 90 responses/min by the fourth session and was only about 40 responses per minute by the fifth. By the sixth session, longer, "nonrhythmic IRTs" had increased in probability accompanied by a slight decrease in the probability of very short ("nibbles") IRTs. By the 11th session, "nibbles" were drastically decreased and the most probable IRTs fell in the bin representing single "misses". For Pigeon 1404, there were increases in the probability of IRTs other than "nibbles" but the structure of responding remained very similar to that under VT (compare to Figure 34).

Figures 59 and 60 show IRT duration as a function of ordinal position for selected sessions. The sessions shown are the same ones that appear in Figures 57 and 58.

For Pigeon 1694, as before, the probability of long, "nonrhythmic IRTs" and misses increased throughout the session. The period, measured in number of responses, during which responding was primarily characterized by

Figure 57. Relative frequency of different IRTS for selected sessions during the transition to the phase in which responses added time to the currently scheduled interval for Pigeon 1694. The ordinal position of the session is indicated in each panel. X-axes: 0.01 s bins; Y-axes: relative frequency.

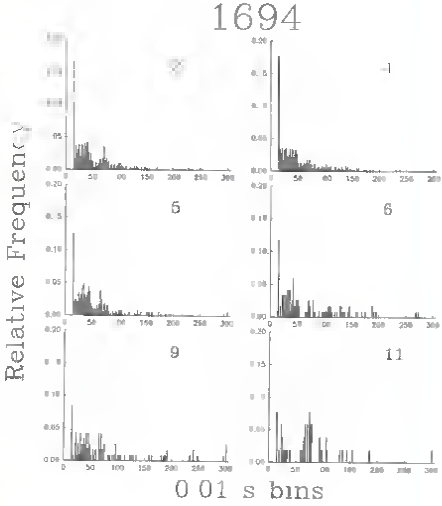

1694
Relative Frequency
0 01 s bins

Figure 58. Relative frequency of different IRTS for the first session during the transition to the phase in which responses added time to the currently scheduled interval for Pigeon 1404. X-axis, 0.01 s bins; Y-axis: relative frequency.

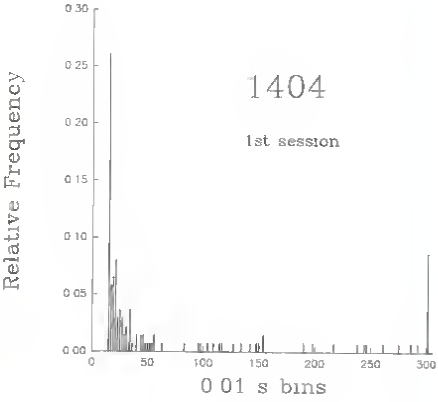

Relative Frequency
0 30
0 25
0 20
0 15
0 10
0 05
0 00
1404
1st session
0
50
100
150
200
250
300
0 01 s bins

Figure 59. IRT duration as a function of ordinal position in the session for selected sessions during the transition to the phase in which responses added time to the currently scheduled interval for Pigeon 1694. The ordinal position of the session is indicated in each panel. X-axes: ordinal position in session; Y-axes: IRT duration in 0.01 s units.

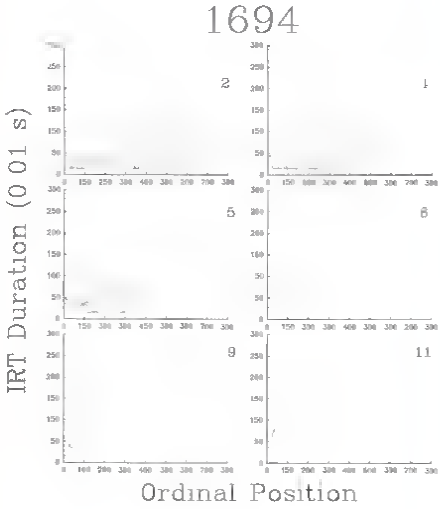
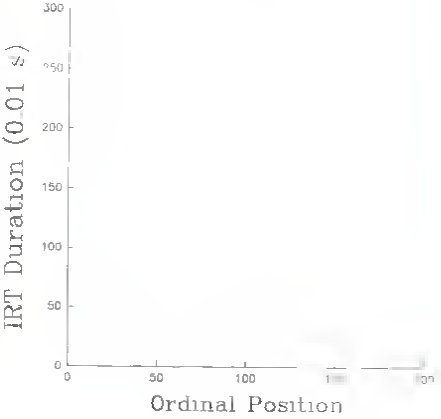

1694
IRT Duration (0 01 s)
Ordinal Position
2
1
5
6
9
11

Figure 60 IRT duration as a function of ordinal position in the session for the first session during the transition to the phase in which responses added time to the currently scheduled interval for Pigeon 1404. X-axis: ordinal position in session; Y-axis: IRT duration in 0.01 s units.


1404
1st session
IRT Duration (0.01 s)
300
250
200
150
100
50
0
0
50
100
Ordinal Position

"nibbles" and 0.3 s (approximately) "pecking movements" decreased across sessions. When there were few responses in the entire session, the increase in probability of misses and nonrhythmic IRTS sometimes did not occur. This can be seen by looking at session 11 (lower right) and also the first session after the return to VT (Figure 63 upper right). Pigeon 1404, during the first session, retained its typical pattern throughout the session.

Overall response rate: return to VT

Figure 61 shows average rate of response as a function of sessions following the return to VT for Pigeons 1694 and 1404. The top panel shows data for Pigeon 1694 and the bottom panel those for Pigeon 1404.

For both Pigeons 1694 and 1404 response rate increased in the first session following the change from positive RTR values back to VT. For the latter, response rate during the first session was at steady-state levels, while for the former this level was not reached until the fifth session.

Molecular description: return to VT

Figures 62 and 63 show IRT distributions for, respectively, Pigeons 1694 and 1404. For Pigeon 1694, the distributions are taken from Sessions 1, 4, 5, and 9, and for Pigeon 1404, Sessions 1 through 6. The sessions were selected so as to show either the whole transition (Pigeon 1404) or to show the transition in cross-section (Pigeon 1694).

Figure 51. Overall response rate as a function of sessions following the return to VT for Pigeons 1694 and 1404. X-axes, sessions; Y-axes: responses per minute.

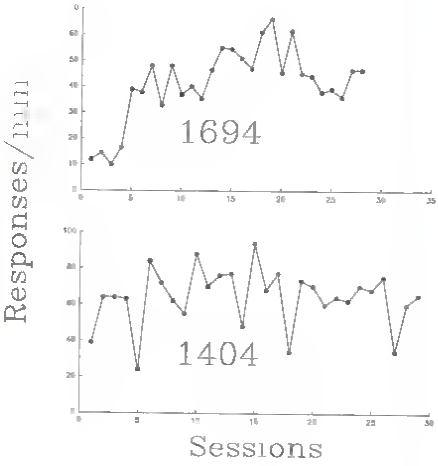

Responses/min
1694
1404
Sessions

Figure 62 Relative frequency of different IRTS for selected sessions during the return to VT for Pigeon 1f94. The ordinal position of the session is indicated in each panel X-axes: 0.01 s bins; Y-axes: relative frequency.

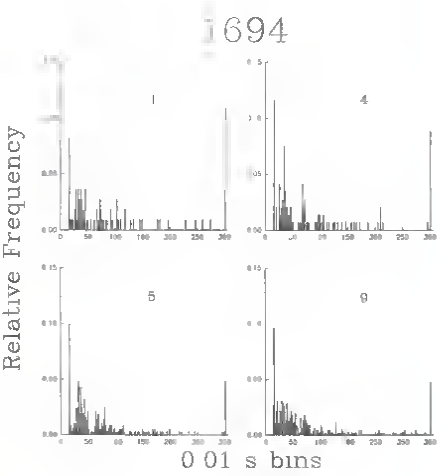
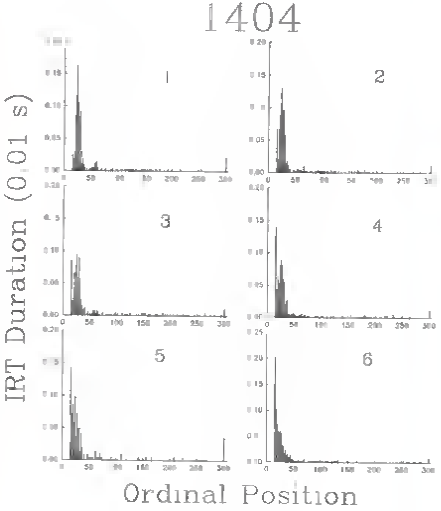

j694
1
4
5
9
Relative Frequency
0 01 s bins

Figure 63. Relative frequency of different IRTS for selected sessions during the return to VT for Pigeon 1404. The ordinal position of the session is indicated in each panel. X-axes: 0.01 s bins; Y-axes: relative frequency.


1404
IRT Duration (0.01 s)
1
2
3
4
5
6
Ordinal Position

During the transition from no responding to the final distributions (top panels of Figure 34) there was, for both pigeons, a period during which responding at the 0.3 s/response rate was relatively more frequent than it was later during the condition. For Pigeon 1694 this type of distribution is similar to the distributions taken from phases in which responses subtracted time (see Figure 33, top left panel). For Pigeon 1404, during the first 2 sessions, the most frequent IRTs were on the order of 0.25-0.3 s, rather than at 0.14 s which characterized this pigeon's pattern of responding throughout the experiment, including the final form under VT. By the sixth session this pigeon's pattern of responding was essentially in its final form.

Figures 64 and 65 show IRT duration as a function of ordinal position in the session for, respectively, Pigeons 1694 and 1404. These figures show the same sessions as Figures 62 and 63.

For Pigeon 1694, under most circumstances, there was an increase, across the session, in long, nonrhythmic IRTs and misses. This feature was not evident in the first few sessions of the transition but emerged by the fifth session. For Pigeon 1404, there appeared to be little change in response patterning within the sessions, as was typical of this subject throughout

Figure 64. IRT duration as a function of ordinal position in the session for selected sessions during the return to VT for Pigeon 1694. The ordinal position of the session is indicated in each panel. X-axes: ordinal position in session; Y-axes: IRT duration in 0.01 s units.

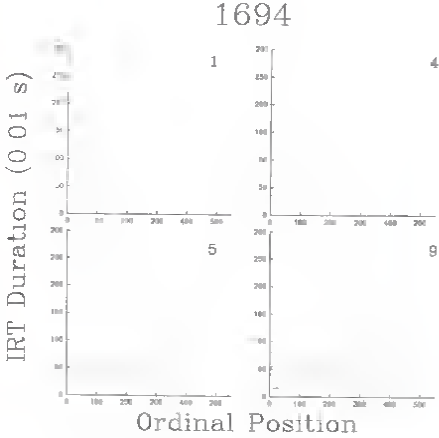
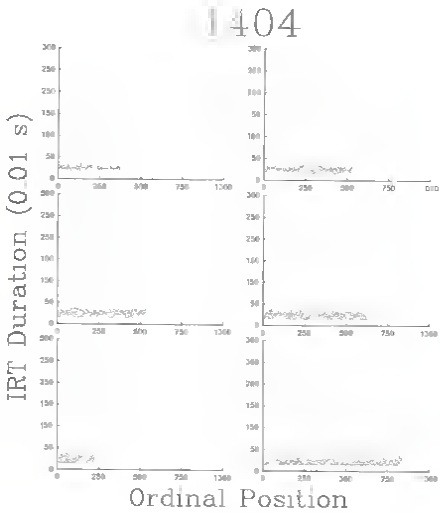

1694
IRT Duration (0 01 s)
1
4
5
9
Ordinal Position

Figure 65 IRT duration as a function of ordinal position in the session for selected sessions during the return to VT for Pigeon 1404. The ordinal position of the session is indicated in each panel. X-axes: ordinal position in session; Y-axes: IRT duration in 0.01 s units.


1404
IRT Duration (0.01 s)
Ordinal Position

Overall response rate: return to VT 300 s, RTE= t s

Figure 66 shows rate of response as a function of sessions for all three subjects. The data are from the return to VT 300 s, RTE= t s.

For all three pigeons response rates rapidly increased to the levels which were maintained previously under this condition. For Pigeons 1694 and 3673, there were a couple of sessions, immediately following the schedule change, in which rate of response was within the range of the preceding stable-state. For Pigeon 1404, however, rate of response during the very first session was about 30 responses/min higher than the highest rate under the stable-state during the preceding VT.

Molecular description: return to VT 300 s, RTE=t s

Figures 67, 68, and 69 show IRT distributions from during the transitions depicted in Figure 66. For Pigeons 1404 and 3673, consecutive sessions are shown and these were taken from the period when response rates were generally increasing. For Pigeon 1694 the first five sessions are shown as well as the 10th session.

For Pigeon 1694, the probability of long, nonrhythmic IRTS decreased across sessions. During this time the relative frequency at the bins corresponding to the 0.3-s rhythm increased only slightly, but the modes began to be more distinctly defined. The nonrhythmic IRTS continued to decrease in relative frequency as the "accuracy" improved.

Figure 66. Overall response rate as a function of sessions following the return to VT 300 s, RTE=t s for all three pigeons in Experiment 2. The value of t was, respectively, for Pigeons 1684, 1404, and 3673, -7.3 s, -7.3 s, and -7.2 s. X-axes: sessions; Y-axes: responses per minute.

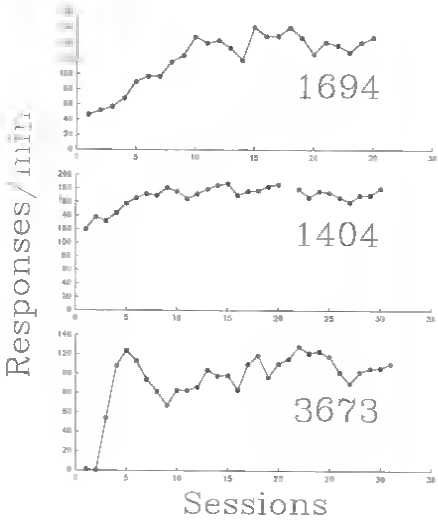

Responses/min
1694
1404
3673
Sessions

Figure 67. Relative frequency of different IRTS for selected sessions during the return to VT 300 s, RTE=-t s for Pigeon 1594. The ordinal position of the session is indicated in each panel. X-axes: 0.01 s bins; Y-axes: relative frequency.

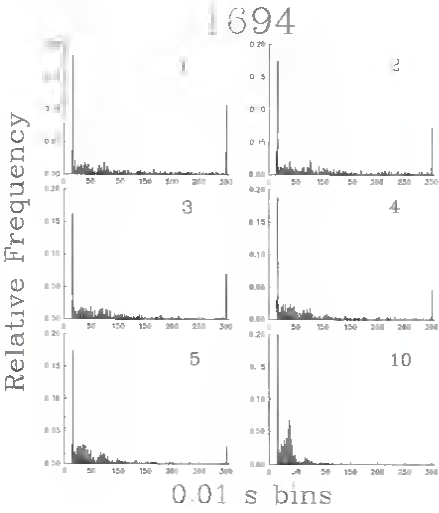

1694
Relative Frequency
1
2
3
4
5
10
0.01 s bins

Figure 6B. Relative frequency of different IRTS for the first four sessions during the return to VT 300 s, RTE=-t s for Pigeon 1404. The ordinal position of the session is indicated in each panel. X-axes: 0 01 s bins; Y-axes: relative frequency.

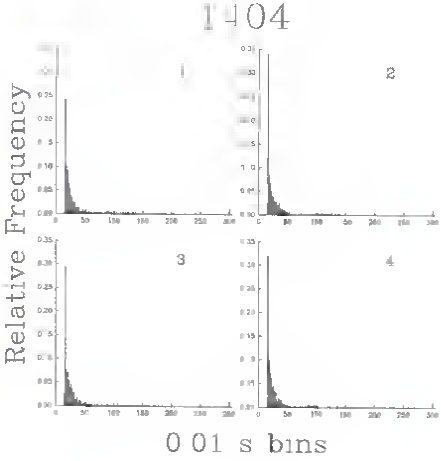
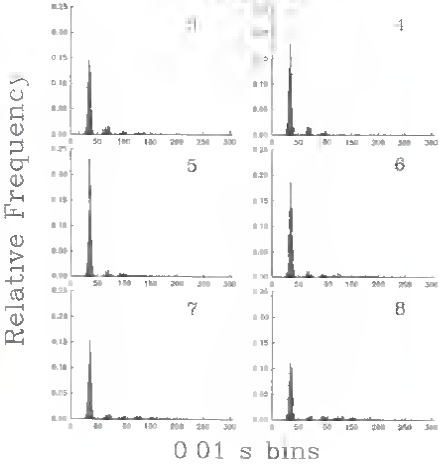

T404
Relative Frequency
0 01 s bins
1
2
3
4

Figure 68. Relative frequency of different IRTs for the third through eighth session during the return to VT 300 s, RTE=-t s for Pigeon 3673. The ordinal position of the session is indicated in each panel. X-axes: 0.01 s bins; Y-axes: relative frequency.


Relative Frequency
0 01 s bins
1
4
5
6
7
8

There was little change in the relative frequency of very short (nibbles) IRTS.

For Pigeon 1404, the distribution for the first session closely resembled that from during the stable state under the early phases in which RTE was negative. That is, there was a mode at the shortest recorded IRT, and the relative frequency declined in a roughly exponential fashion thereafter. The distribution changed very little after this point. As soon as there was any appreciable amount of responding in a session (session 3) the associated IRT distribution was virtually indistinguishable from its final form. Once responding began, it was essentially intact. As can be seen in Figure 69, once Pigeon 3673 began responding, the IRT distribution was virtually indistinguishable from those from VT 600 s and RTE=-15 s. Recall that there was no difference between VT 600 s RTE=-15 s and VT 300 s, RTE=-t s in any dimension of responding. Recall that t was, respectively, for Pigeons 1694, 1404, and 3673, 7.3 s, 7.3 s, and 7.2 s.

Figures 70, 71, and 72 show IRT duration as a function of ordinal position in the session for, respectively, Pigeons 1694, 1404, and 3673. The sessions for which data are displayed are the same ones as in Figures 67, 68, and 69. As before, latencies and IRTS greater than 300 s were not plotted.

Figure 70. IRT duration as a function of ordinal position in the session for selected sessions during the return to VI 300 s, RTE=-t s for Pigeon 1694 The ordinal position of the session is indicated in each panel X-axes: ordinal position in session; Y-axes: IRT duration in 0.01 s units.

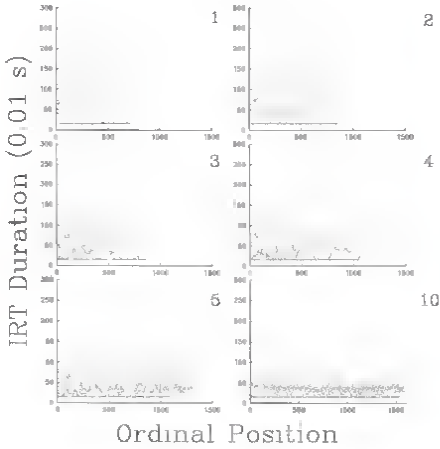

1694
1
2
3
4
5
10
IRT Duration (0.01 s)
Ordinal Position

Figure 71. IRT duration as a function of ordinal position in the session for the first four sessions during the return to VT 300 s, RTE=-t s for Pigeon 1404. The ordinal position of the session is indicated in each panel. X-axes: ordinal position in session; Y-axes: IRT duration in 0.01 s units.

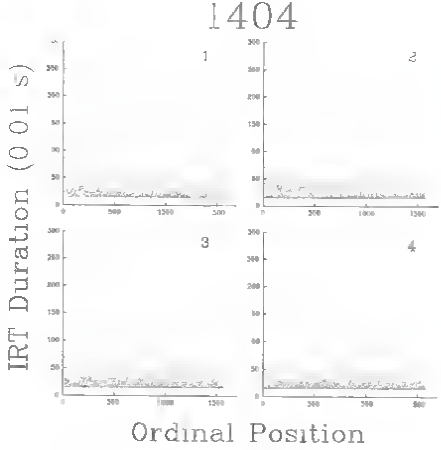
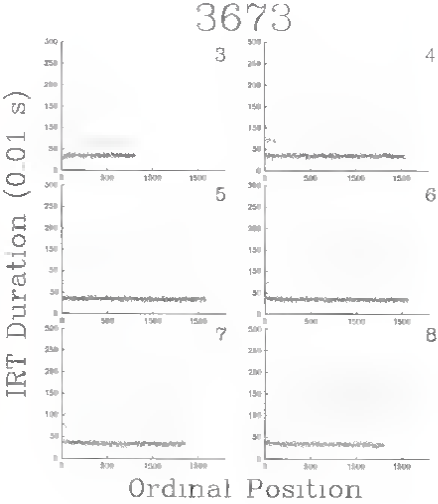

1404
IRT Duration (0 01 s)
1
2
3
4
Ordinal Position

Figure 72. IRT duration as a function of ordinal position in the session for the third through eighth session during the return to VT 300 s, RTE=-t s for Pigeon 3673. The ordinal position of the session is indicated in each panel. X-axes: ordinal position in session; Y-axes: IRT durations in 0.01 s units.


3673
3
4
5
6
7
8
IRT Duration (0.01 s)
Ordinal Position

For Pigeon 1694, IRT durations appeared equally distributed throughout the session for the first two sessions. After this point long IRTS were slightly more probable later in the session.

For Pigeon 1404, the probability of long IRTS decreased across the session for all of the four sessions shown. In this sense the entire transition is not completely depicted since, while a given session may show increases or decreases in the probability of particular classes of IRT durations, each sessions appear roughly equally distributed.

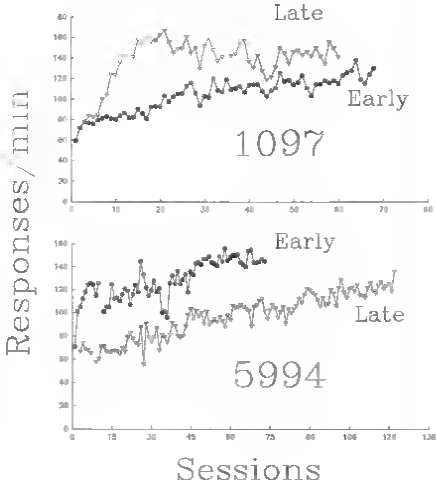
For Pigeon 3673 there was, by the fourth session, an increase in probability of long, nonrhythmic IRTS throughout the session--or, at least, there was a period during which long IRTS were relatively rare. During this portion, "accuracy" also tended to be better. These two features were also characteristic of the stable-state.

Changes in the Character of Transitions

This final section is concerned with the data of Pigeons 1097 and 5994. These two pigeons showed changes in the character of transitions to experimental phases and\or changes in the VI baseline.

Figure 73 shows two transitions each for Pigeons 1097 and 5994. One of the two transitions for each subject was from "early" in the experiment and the other from "late." For both pigeons, the schedule to which the VI 60 s was changed was the same one in terms of "percentage VR"; 98% and 90% for, respectively, Pigeons 1097 and 5994

Figure 73. Overall response rate as a function of sessions during transitions from baseline "early" and "late" in Experiment 1 for Pigeons 1087 and 5994. X-axes: sessions; Y-axes: responses per minute.

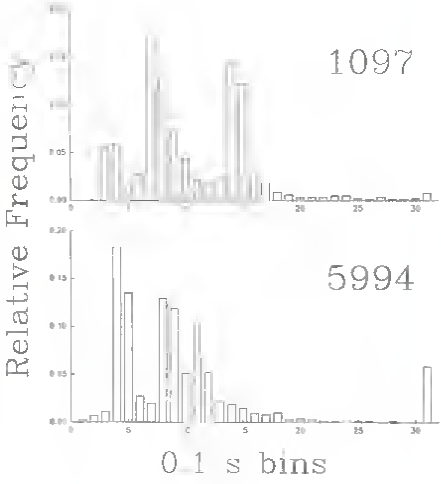

Late
Early
1097
Early
Late
5994
Responses/min
Sessions

For Pigeon 1097, the first exposure to a 90% VR schedule (VI 3000 s, RTE=-49 s) produced only slight increases in rate of response during early sessions, followed by a slow increase across sessions. In contrast, later transitions were characterized by dramatic increases in response rate, with near maximum rates reached within about 20 sessions. The "late" curve shown was following a schedule change to the exact same schedule (not just the same percentage of VR) as the "early" curve.

For Pigeon 5994, the first exposure to a 90% VR schedule (VI 600 s, RTE=-7.5 s) produced a change in response rates very similar to the late transitions for Pigeon 1097. Subsequent transitions were, however, more similar to the early transitions of Pigeon 1097. The "late" curve was also from a transition to a 90% VR schedule but the RTE parameter was larger (-15 s) since the baseline rate of response was lower.

Figure 74 shows IRT distributions for Pigeons 1097 and 5994. The distributions were from the last session of VI 60 that immediately preceded the transitions depicted in Figure 68 ("Early"). This figure may be compared to the top panels of Figures 16 (Pigeon 1097) and 14 (Pigeon 5994). The middle panel of the three in each of these latter figures is particularly important as it shows the distribution which immediately preceded the "late" transitions in Figure 73. For Pigeon 1097 the IRT distributions reveal a possible "explanation" for the differences in transitions. The top

Figure 74. Relative frequency of different IRTS from the last session of baseline preceding the "early" transitions depicted in Figure 73 for Pigeons 1097 and 5994. X-axes: 0 1 s bins; Y-axes: relative frequency.


Relative Frequency
1097
5994
0.1 s bins

panel of Figure 74 is, in some respects, different than the middle panel of Figure 16. The mode at about 1.5 s in Figure 74 is quite prominent, whereas in the middle panel of Figure 16 it is quite small. In the latter Figure, too, there is a much more prominent mode nearer to 2.0 s. The top panel of Figure 74 more closely resembles the top left-hand panel in Figure 16 and this provides further evidence that one or both of the two above-mentioned properties of the distributions were important. The top left-hand panel of Figure 39 shows the transition to VR and this phase was initiated the session following the one depicted in the top left of Figure 16. (The top right-hand panel of Figure 39 shows the same function which is labeled "late" in Figure 73.) This transition is intermediate to those shown in Figure 73; there was a rapid increase as in the "late" curve, but this is followed by a slow increase to the stable-state as in the "early" curve.

For Pigeon 5994, the IRT distribution under VI remained relatively stable over the course of the experiment (recall that the distributions constructed on the basis of 0.1 s bins should be shifted about 0.05 s to the left because of a data collection error). The only apparent difference is that, preceding the later transitions shown in the top panel of Figure 16, there was a fourth mode around 1.2-1.3 s.

CHAPTER 4

DISCUSSION

Overall Response Rates: Stable-States

For all six pigeons whose data are reported here, diagonal movement through the schedule space was associated with increases in rate of response (see Figures 14 and 32). This finding is in general agreement with other studies investigating interlocking schedules, especially Powers' (1968) and Rider's (1977). The present studies, thus, extend the generality of this finding to pigeon subjects and to interlocking schedules where the base-interval or time-schedule was composed of variable time intervals. Experiments 1 and 2 do not, however, provide an exact specification of the shape of the surfaces which result when rate of response (or maximum rate of response) is plotted as a function of 2 or 3 of the parameters, or the form of the equations which describes them. There are, however, enough data to make speculation fruitful.

For this discussion only manipulation of RTE and EI will be considered and only values of RTE equal to, or less than, zero will be considered. The two, 3-dimensional, surfaces formed when rate of response (or maximum rate) is plotted as a function of RTE and EI with a=0 or with a=∞ appear quite similar or, at least, the data collected so far

do not show them to be substantially different. The discussion will be relevant to both of them.

The data collected so far using schedules from these spaces suggest three features of importance. First, some portions of the spaces around RTE=0 are relatively flat. Small diagonal movements away from RTE=0 (RTE decreases and BI increases) can result in little change in response rate. Decreasing RTE while holding BI constant, too, may not produce increases at some levels. This is particularly clear in the data for Rat 3 (only the data for Rats 1 and 3 can be unambiguously interpreted) in Berryman and Nevin (1962).

Secondly, some portions of the spaces are very steep. Small diagonal movements (RTE decreases and BI increases) can produce large increases in rate of response. This feature is observable in most of the interlocking-schedule data presented so far.

Finally, there is some point at which diagonal motion through the spaces (RTE decreasing and BI increasing) no longer results in increases in rate of response. This feature is, again, observable in most of the interlocking-schedule data. It is evident when response rates under different interlocking schedules are compared and when these data are compared with those from the conditions where ratio schedules were imposed.

These three facts suggest that rate of response, when BI is held constant, is an s-shaped function of $-\log(RTE)$ when

RTE is decreased from 0. This function would, presumably, change systematically as BI is changed. This statement, however, requires a great deal of qualification; in the absence of data from certain kinds of experimentation it is not clear that rate of response is a continuous function of RTE at all BI values. Both continuous and discontinuous models are discussed below.

If response rate (or maximum rate) is, in fact, a continuous function of RTE at all BI values then an algebraic expression could describe the shape of the surface created when response rate is plotted as a function of RTE and BI. A standard form, which constitutes the core of the more complete description presented below, is:

$Y=(NM)/[N+(M-N)e^{-Rx}]$.

This equation produces an s-shaped function of X, which is -RTE and this core equation is relevant to a constant BI value and changing RTE value. N controls the length of the horizontal portion which precedes the first inflection point, and has the dimensions 1/time; it might be viewed as related to the threshold level of RTE which produces a measurable increase. R, which also has the dimensions 1/time, is the growth constant and controls the slope of the function between the two inflection points, and M, which has dimensions 1/time controls the asymptote. In the more complete equation below, M reflects the difference between a maximum rate of response and the rate of response at the particular constant BI value and RTE=0.

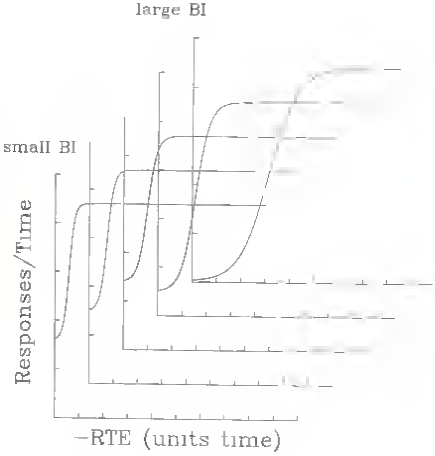
The above equation--when combined with a transformation of the VI "input-output" function (i.e., rate of response as a function of the rate of reinforcement under VI schedules) in terms of interval values instead of rate of reinforcement--can be used to describe the data from the interval-ratio continuum. The same form combined with a transformation of the VT "input-output" function (i.e., the function relating response rate to VT parameter) would be used to describe data from the related space where a=0. The rate of response at RTE=0 is simply given by the transformed "input-output" function and this amount is, essentially, added to the amount given by the above equation. That is:

$$\text{resp. rate} = (VI-N)+(NM)/[N+(M-N)e^{-R(M-N)}]$$

where VI is the rate of response under a given value of BI and RTE=0. In a complete treatment, both N and R might be expected to be, themselves, functions of BI. For example, the flat portion around RTE=0 probably gets broader as BI is increased because the same RTE value would constitute a smaller proportion of the interval. The function might also be expected to rise more slowly at higher BI values for the same reason.

Figure 75 shows 5 cross-sections perpendicular to the BI axis in the interval-ratio space (BI is constant in each cross-section and rate of response is plotted as a function of -RTE. Each cross-section has a different "growth parameter"; R gets smaller as large BI values are approached. N was held constant for simplicity but this is

Figure 75. Hypothetical curves representing response rate or maximum response rate as a function of RTE and SI. Small SI values appear in "near" panels and large SI values in "far" panels. X-axis: RTE; Y-axis: rate of response; K-axis SI value.


large BI
small BI
Responses/Time
–RTE (units time)

not a stipulation of the "theory." Notice that the y-intercept of each cross-section is a point on the transformation of the VI input-output function. In the space where a=0, the y-intercepts would lie on the transformed VR input-output function. For subjects in which VR schedules do not support responding this function would be constant at zero. The form of the equations describing the a=0 space would be the same as the a=infinity space but the equations themselves would not be the same. Specifically, M and R might be expected to differ.

The main problem with the above conception is that it is inconsistent with some of the data presented by Berryman and Nevin (1962), particularly those for Rat 4. Recall that for Rat 4, rate of response decreased as RTE was decreased from zero at BI 120 a. For Rat 2 this may also have been the case but, with no indication of the variability around these points, it is difficult to say if this can be taken seriously. In any event, as was mentioned earlier, it is quite possible that the high rates under FI 120 a were the result of the immediately prior exposure to FR 36; that is, while stable-states may have been observed, the overall shape of the surface may not have been stable. Stability of the surface can be, at least reasonably, assured by redetermining some of the stable states. If Rat 4's data are eliminated and, for Rat 2, the difference between FI 120 a and the two interlocking schedules with BI=120 a is downplayed, the data in all of the experiments are

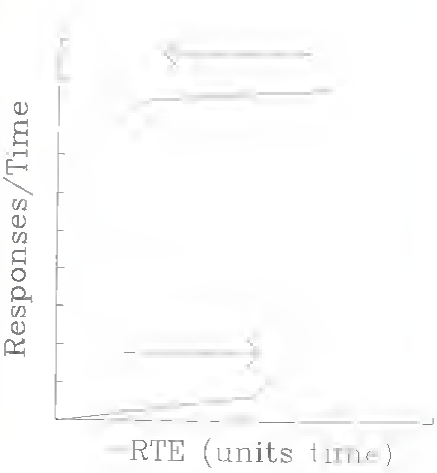
consistent with the conception presented here. Given the latitude of the theory, it is likely that the s-shaped function would, indeed, provide a reasonable fit. It should be added that this equation is intended only as a starting point in the endeavor to describe the relevant portion of the space.

A discontinuous model that is consistent with the data collected so far is provided by a special branch of dynamical theory known as Catastrophe Theory (Thom, 1975). According to this theory, systems with two parameters (or "control factors") for which the notion of *potential* is relevant, will show certain kinds of behavior; namely hysteresis and bistability. Relatedly, the surfaces which result from plotting a dependent variable as a function of the two parameters of such systems, contain regions in which there are no stable-states. Although Catastrophe Theory, per se, deals with systems for which the notion of potential is relevant, there are other systems that produce similar behavior but for which there exists no potential (Prigogine, 1980). The "cusp catastrophe" which is relevant to this discussion is difficult to depict; part of it can not be described by a function since the surface is "folded" and there are, thus, more than one y-value for a given x-value (i.e, it is not a function). One may visualize this space, however, by looking at Figure 75 and imagining the curves progressively becoming *literally* s-shaped. The curves depicted in Figure 75 are frequently referred to as

s-shaped, as they were in the above discussion, but they do not actually "fold back" on themselves as the letter "s" does. It is not necessary to show the folded portion, however, since this portion represents unstable states. Figure 76 shows the stable states that might be expected to occur at some places in such a system. The bottom curve shows the stable-states that result from increasing the absolute value of RTE (recall that only RTE values less than or equal to zero are being considered) from near zero, while the top curve shows the stable-states that result from decreasing the absolute value of RTE towards zero.

There are a few reasons to believe that Catastrophe Theory--or something like it--is relevant to the spaces under consideration. Catastrophe Theory holds that any system governed by a potential and having two independent variables controlling it must, at some parameter values, show bistability and hysteresis. Furthermore, systems for which the notion of autocatalysis is relevant, frequently show bistability and hysteresis (Nicholas & Prigogine, 1989). Both possibilities have been suggested. Killeen (1982) has suggested that the notion of potential is relevant to behavior, and Forster and Skinner (1957) suggested that the notion of autocatalysis is relevant. The former might be considered somewhat speculative but the latter is almost certainly true. Both molar and molecular perspectives on, for example, VI-VR differences seem inherently to embrace this notion. If a schedule is changed

Figure 76: Hypothetical curves showing discontinuous stable-states in a cross-section of the surface formed when response rate is plotted as a function of RTE and RI. The bottom curve occurs when RTE is decreased from 0, and the top curve results when RTE is increased towards 0 X-axis: RTE; Y-axis: rate of response


Responses/Time
RTE (units time)

from VI to VR different, shorter IRTS will be reinforced and response rate will increase. This produces a state in which still shorter IRTs are reinforced, etc, i.e., an autocatalytic process. From a molar perspective, as was discussed in the Introduction, rate of response increases when an interval schedule is changed to a ratio schedule because it allows increases in rate of response to produce an increase in rate of reinforcement which in turn results in a higher rate of response and so forth, i.e., another sort of autocatalysis.

In addition to the largely conceptual reasons given, there are some data which bear on the issue. It has been suggested, for example, that the function that relates rate of response to ratio value is an inverse, but discontinuous function (Baum, 1993). As the ratio value increases there are continuous decreases in rate of response. When large ratio values are reached, however, rate of response may abruptly drop to zero. Such a situation resembles that of the top curve in Figure 7b. If, in fact, rate of responses fell absolutely to zero, however, increasing the absolute value of MTE (by decreasing it from zero) would not be expected to result in the lower curve in Figure 7b. This is because there would be no way for the change in contingencies to "contact" behavior. This consideration alone suggests that the first "model" suggested would not hold at RI values which, when MTE=0, result in no responding. This is because there is not a provision that

accounts for bistability and hysteresis. This finding, however, does not lead to a full endorsement of the cusp catastrophe. If, however, one was dealing with BI values small enough so that some responding still occurred at RTE=0, the result of decreasing RTE below zero could very well be represented by the lower curve in Figure 76. In addition to the data from ratio schedules, Berger (1988), found evidence of hysteresis using schedules from a continuum similar to the one examined here (see Introduction). Although Berger did not manipulate parameters in both directions within-subjects, groups of subjects experienced the conditions in the opposite order. Subjects first exposed to the ratio contingencies tended to have higher rates throughout the experiment. Although the contingencies arranged by Berger (1988) cannot be described exactly in terms of RTE and BI, estimates can be made on the basis of the feedback functions generated by the two systems. When this is done and the data (response rates) from Berger (1988) are plotted in terms of the estimates of RTE and BI, the graphs are remarkably similar to those from Experiments 1 and 2. Figure 77 shows responses/session (session time was fixed) as a function of the estimates of BI and RTE for rats in Group A in Berger's experiment. The data from the FR 50 condition (X=1 and C=50) are shown as a horizontal line on the back panels.

Both of the conceptions presented above ignore certain features of the data from the interval-ratio and time-ratio

Figure 77 Responses per session for rats in Group A of Berger's experiment. The data from the FR 60 condition (X=1 and C=60) are shown as horizontal lines on the "back" panels. No point is plotted for the ratio-schedule data in order to remind the reader that this point would not be in the space segment shown. X-axes: RTE. Y-axes: responses per session. Z-axes: BI.

Responses/Session
A1
A2
A4
A5
R T E (s)
B I (s)

spaces. They ignore the fact that as any schedule approaches FR 1, rate of response decreases (Baum, 1993). Thus, at small ratio and interval schedules, neither conception will likely hold. The conceptions also deal only with rate of response averaged over many sessions or maximum rates of response. At this point, the theories say nothing about the issue of "deviations from a steady-state" (Skinner, 1938).

All six pigeons whose data are reported here showed apparently chronic, nonrandom, but nonperiodic oscillation in rate of response which was, in general, most apparent under interlocking and ratio schedules. Although Skinner (1938) discussed the issue of stable oscillations at some length it has, with a few notable exceptions, been all but ignored. This is surprising because wherever the issue has been addressed such oscillations have been noted (Cumming & Schoenfeld, 1960; Palya, 1992; Skinner, 1938; Zeiler & Davis, 1978). Skinner (1938) and Zeiler and Davis (1978) discussed oscillations in FI schedules, Cumming and Schoenfeld (1960) discussed them in T-tau schedules and Palya reported data from VI, VR, FI, FR, IRT>t and IRT<t schedules. Palya (1992) presented data from one pigeon for which keypecking was maintained for 780 sessions on a VR 150 schedule. These data, from about session 150 to 780, showed variability closely resembling that for the pigeons in the present Experiments 1 and 2 (See Palya, 1992, Figure 2, 4th panel from the top in the rightmost column). In addition to

the kind of oscillations shown for the birds in Experiments 1 and 2--oscillations on the order of 20-50 sessions--the bird in Palya's experiment showed evidence of an extremely low-frequency oscillation on the order of 400-500 sessions.

The importance of the oscilatory aspect of responding over long units of time cannot be overstated. It makes questionable the effort to characterize rate of responding (and other dependent variables) as an average of even several sessions. Indeed, the very notion of a "steady-state" appears largely irrelevant to behavior (the term "steady-state" is best applied to time series in which there are no systematic trends). The notion of "stable-states," on the other hand, is relevant (the term "stable-state" refers to the long term imperturbability of a time series). Behavioral stable-states, in fact, appear remarkably resilient. Were this not so, the experimental analysis of behavior would be quite difficult. Even where it is necessary to characterize stable responding as a single number (which will be frequently) it is wrong to imply that this number represents the "true" level of a dependent variable, for there is no single "true" level. At best, a value may be determined which represents the level around which the dependent variable oscillates. There may, however, be some good reasons for maintaining traditional kinds of stability criteria. If, for example, phase changes are initiated only when the last five sessions do not differ much from the previous five, then they will be initiated,

hopefully, only at times when the confluence of controlling variables is similar. It would, however, still be necessary to pay attention to the level of the dependent variable since the relationship between the last five sessions and the preceding five may be the same when the dependent variable is "steady" at the "top" of an oscillation as well as at the "bottom." It would, further, still be necessary to have some idea as to the range of variation within the entire stable-state in order to judge whether the new experimental phase has produced a different stable-state.

It should be pointed out that much of the preceding discussion is based on the notion that some systematic variation is "inherent" in the condition. This view has been vigorously attacked by Sidman (1960), and Johnston and Pennypacker (1980). There are a few general reasons, however, to question the validity of these criticisms. First, and most importantly, when dealing with even rather simple systems, there is no reason to suspect that a "steady-state" will result from prolonged exposure to a condition. Even in systems where there cannot be measurement error, or "noise" due to uncontrolled variables (i.e., mathematical and logical systems), oscillation is common. For continuous systems, in three dimensions or more, there is no guarantee that the oscillation will even be periodic (Abelstein-Keshett, 1988, Gleick, 1987). From a strictly mathematical point of view, it would be exceedingly surprising if some of the variation in behavioral systems

was not "inherent." The position that all variation is "imposed" is a philosophical position. Although the position is effective in countering the notion that behavior, particularly human behavior, is not amenable to standard scientific practice, it is risky because it rules out the kind of inherent systematic variation which is known to occur in some biological systems (Glass & Mackey, 1988). The term "inherent" should not necessarily be taken to mean "inherent in the organism." It may be inherent in the organism-environment feedback system. Some variation may, however, be "inherent" in the former sense; a lack of variation in a behavioral system would render the system insensitive to a change in conditions and processes may have developed to insure that operants do not become too stereotyped. There is, further, a reason specific to the experiments reported here, to think that the systematic variability is inherent in the condition; although the general character of oscillation seemed sometimes to be similar across subjects, the direction of the local "trends" did not appear to be synchronized as they would be if the trends were due to features of the apparatus, such as changes in the force required to operate the key, or the setting of the feeder potentiometer, etc. Systematic variability could still be due to variation in handling procedures, "home cage" conditions, or other features of the pigeons' environments extraneous to the experiment per se. It is, however, difficult, but not impossible, to see how

these types of variables could result in such long-term trends.

There do not appear to be simple solutions to the methodological problems raised by the fact of chronic oscillation if such oscillations are "inherent." If experimental phases are maintained long enough to establish unequivocably the nature of the stable-state engendered, experiments could take years to complete. Although experimenters interested in some questions probably need not adhere to such rigid criteria, it is not clear as to what criteria they should adhere. Certainly a great deal of work is necessary to resolve the issue; experiments must be undertaken which have as their goal the understanding of the stable-states engendered by various procedures and how variables have impact on the behavior at different points within trends.

The first step in this important endeavor is the establishment of a large enough data base to allow general descriptions to emerge. Palya's (1982) work, as well as that of Skinner (1938), Cumming and Schoenfeld (1960) and Waller and Davis (1978) are important steps in that direction. In addition to somewhat qualitative description of these data, more quantitative techniques such as Fourier transform, autocorrelation, and similar methods should be applied in order to assess the nature of any sequential dependencies or regular oscillations that might exist. In terms of deciding whether or not some variation is inherent,

It will probably be necessary to investigate directly some of the putative extraneous variables frequently said to produce variation, and to investigate levels of those variables that are commensurate with what subjects are likely to experience. There is no question, for example, that changing the force required to operate a lever or key or changing the level of deprivation will affect behavior, but it is not clear that very small changes in such variables will do so. It is even less clear that even rather substantial changes in temperature, humidity, or other "extra-experimental" variables can substantially affect behavior. On the other hand, most experienced researchers are familiar with substantial effects which appear to be correlated with the particular person handling the subject prior to the experimental session per se.

Overall Response Rates. Transitions

It is difficult to characterize all of the transitions in Experiments 1 and 2 in any general way. There was, however, one description that seemed to hold; where rate of reinforcement changed upon a change in schedule (independent of changes in rate of response) transitions tended to be rapid. Schedule changes that did not immediately result in changes in reinforcement rate sometimes resulted in rapid changes in response rate, but not necessarily so. Response rate decreased rather slowly for 2 out of the 3 pigeons in Experiment 2 when VT 300 s, RT2=t s was changed to VT where the VT parameter "matched" the average rate of reinforcement

under the preceding condition. Similarly, in Experiment 1, Pigeons 5994 and 2760 tended to show slow transitions between VI and interlocking/ratio schedules. In both of these phase changes reinforcement rate and number of responses per reinforcer were matched at the time of the phase change. In every condition, however, in which reinforcement rate changed independently of response rate, the transitions can only be judged as relatively rapid.

The character of the transitions from VI to interlocking/ratio schedules provide some support for notion that Catastrophe Theory may be relevant to the schedule spaces. The transitions could be very slow or very rapid. Recall that Catastrophe Theory predicts that some places in the 3-d space (one dependent and two independent variables) will consist of a continuous set of stable-states while other places will contain nonstable-states. If the independent variables are changed such that the system passes through the unstable portion the dependent variable would be expected to change quite rapidly. If they are changed so that the system passes through the portion containing all stable states, the dependent variable might be expected to change much more slowly. Further, both slow and rapid changes could occur within the same subject and the same transition as with Pigeon 5994.

There was some evidence that aspects of the transitions from VI 60 s to interlock/ratio schedules depended on the parameters of the interlock/ratio schedules. This relation

was not, however, a simple one. For Pigeon 1097, there was an orderly relation between the "percentage of VR" and the rate of change in response rates during the first 10 sessions. The most rapid changes during the first 10 sessions occurred for 100% (VR), the second most rapid under 95%, the third under 75%, and the least change during the first 10 sessions occurred under 50% (see Figure 12). No such order was observed for Pigeon 5554 during the first 10 sessions. There was, however, evidence of a similar order if one considers the experimental phases which produced equivalent maximal rates (i.e., 100 and 90%). Pigeon 5554 reached near maximal rates in about 60 sessions under VR 60 but did not do so until about 120 sessions under 90% (see Figure 39, bottom 2 panels). Further, only under VR did 5554 show the kind of dramatic increase that characterized the data for Pigeon 1097. Starting at about session 50, response rate increased from about 70 responses/min to nearly 140 responses/min by session 60 for Pigeon 5554. For Pigeon 1097, however, this same order was not observed. That is, rate of response reached nearly 160 responses/min within 20 sessions under 95 and 75%, but did not do so for VR until about session 40. Under 50%, rate of response was not higher than 150 responses/min until near session 50. It was, however, suggested that the transition to VR 51 was similar to both earlier transitions, in which there were no dramatic increases, and the later ones that followed it where there were no slow increases. It is possible that if

VR had been imposed again the transition would have been more similar to, or even more rapid than, those occurring for 98 and 75%. An alternative interpretation is that schedules within a continuum which generate equivalent stable-states will produce equivalent transitions. In that case the differences observed in the present experiment represent the range of variation in the rate of change. A first step in investigating these alternatives would be to perform experiments involving repeated transitions between the same schedules, for example, VI 60 s to matched VR schedules. Such experiments would reveal the nature of changes across successive transitions, as well as the range of variation that could be expected when a steady- or stable-state of transitions is produced. Such an experiment could be seen as important to investigations of the rate of change in response rate as a function of schedule parameters; it seems likely that once a steady- or stable-state of transitions has been produced with one set of experimental parameters there would be little systematic trend if another schedule parameter was used. This proposition could, of course, be directly investigated by following, for example, repeated transitions between VI and VR with repeated transitions between the same VI schedule and an interlocking schedule.

Molecular Data: Stable-States

A striking feature of the molecular data is the prevalence of IRTS at approximately 0.3 s and integral

multiples thereof. For four of the six pigeons whose data are reported here the preponderance of responding (at least under response dependent schedules) was of this type. Even for the two pigeons (1404 and 2760) whose data could not be so characterized, this pattern of responding emerged at some point in the experiments. For Pigeon 1404, it emerged when VT was reinstated and for Pigeon 2760 it emerged during the phase in which RTE was a function of responding. It is likely, however, that Pigeon 2760 pecked at this rate but only infrequently hit the key. In Figure 3B, two bands are clearly visible between 1.0 and 1.5 s. Further, informal visual inspection of this pigeon corroborated this interpretation. For two of the six pigeons (1404 and 1694) a large preponderance of IRTs were on the order of 0.14 s. This type of rhythmic responding probably represents a fundamentally different motion--opening and closing of the beak as opposed to back-and-forth motions of the head and neck. This interpretation is plausible given the topography of elicited (autoshaped) keypecks where food is the unconditional stimulus (UCS). Jenkins and Moore (1973) photographed such autoshaped keypecks and found that the pigeons' beaks were usually open. This was in contrast to autoshaped keypecks where water was the UCS. Smith (1974) found that pigeons could operate a standard pigeon key by chewing the beak. Such IRTs could be as short as .03 s. In addition to this fact, pigeons typically eat by pecking straight down at the food and then grasping it in their beak

(Premack & Kilpec, 1961). Although none of the pigeons in the current experiments were photographed or observed systematically, informal observation of the pigeons, especially 1404, revealed that the key was sometimes operated by opening and closing the beak. The occurrence of IRTs shorter than 0.2 s have been reported both by Gentry, Weiss, and Latles (1983) and by Palya (1992). Both Palya (1992) and Gentry, Weiss, and Latles (1983) found such IRTs to be rather common under FI schedules once responding had begun. Palya (1992) found that they were essentially absent under VI but present under VR and FR. These findings are in general agreement with the data reported here. In Experiment 1, IRTs shorter than about 0.25 s were rare under VI and relatively more common under interlocking/ratio schedules. For Pigeon 1097, such short IRTs and those in the 0.3 s band formed one solid band extending from 0.14 to about 0.4 s.

The IRT distributions under VI and interlocking/ratio schedules were somewhat different from each other, especially for Pigeons 1097 and 5894. Under VI there were more IRTS that did not represent the fundamental 0.3-s motion and more IRTS that were integral multiples of it (IRTs that contained "misses"). In addition, there were more IRTS "in between" the modes at about 0.3 s and integral multiples thereof. The difference in "nibble" between VI and interlocking/ratio schedules have already been mentioned. The above findings were in general agreement

with those reported by Blough (1963), Gentry, Weisa, and Latiea (1963) and Palya (1992). There was, however, at least one difference. All of the pigeons in Palya's (1992) experiment and both pigeons in Gentry, Weisa, and Latiea (1963) experiment emitted IRTS in the 0.3 s category under stable-state conditions. The exceptions in the present experiments have already been mentioned. No pigeons in Blough's (1963), Gentry, Weisa, and Latiea' or Palya's (1992) experiment were exposed to response-independent schedules as in Experiment 2. Only 2 of the 3 Pigeons (1694 and 1404) whose data are reported from Experiment 2 responded reliably under VT. Neither of these two pigeons showed a great deal of responding at the 0.3-s rhythm under VT. For Pigeon 1404, this was not surprising since it did not respond in this fashion (except transiently--see below) under portions of the experiment where RTE was negative. Pigeon 1694, on the other hand, did respond an appreciable amount at the 0.3-s rhythm under conditions of response dependency. For both of these pigeons there was a still a great deal of responding at the rapid ("nibbles") rhythm. Pigeon 1694 did, apparently, still emit some IRTS in the 0.3-s rhythm but the distribution tended to be flat after the large mode at about 0.14 s. What responding there was between this mode and about 0.75 s was rather "inaccurate".

During stable-states two kinds of fluctuations were possible; those occurring between sessions and those occurring between reinforcements. Although there were some

individual differences in within-interval changes, there were many commonalities. Average IRT duration as a function of ordinal position postreinforcement appears in Figures 22, 23, and 24 for Experiment 1 and in Figures and in Figure 35 for Experiment 2. Under VI 60 s (Experiment 1) average IRT duration tended to be shortest immediately (Pigeons 5894 and 2760), or shortly after (Pigeon 1097), reinforcement, and to increase for all, or part of the remaining interreinforcement interval. For Pigeon 1097, average IRT duration tended to decrease for the first 10-15 responses and then to increase across the next 20-30 responses. For this pigeon there also appeared to be oscillations in average IRT duration across the interreinforcement period. Under interlocking/ratio schedules, average IRT duration tended to be shortest immediately after reinforcement and to increase slightly over the next 20 or 30 responses, or remain constant. The extent of the increase, where it did occur, was very small. For Pigeon 1097, there was a tendency for average IRT duration to decrease slightly over the first few responses and to increase thereafter. In Experiment 2 during conditions of response dependency (RT$<0) the within-session changes were very similar to those in Experiment I under interlock/ratio. The increases in IRT duration, where they occurred, appeared to be the product of an increased probability of long IRTs not related to the rhythmic responding. IRT duration (not averages) as a function of ordinal position appears in Figures 25, 26,

and 27 (Experiment 1) and in Figure 37 (Experiment 2). There have been few studies of the systematic change (or lack thereof) in IRT duration across interreinforcement periods in variable-interval and variable-ratio schedules with which these data may be compared. Kintsch (1965), however, using 2 rats as subjects, compared VI 40 s and VR 15. Under VI, Kintsch (1965) found no statistically significant change in IRTs across the first 30 responses (this was all he analyzed), although both rats did show a downward trend with oscillations. These data were, thus, essentially inconsistent with the data presented for Experiment 1, although Pigeon 1097 did show a downward trend in average IRT for the first 10-15 responses. It is somewhat difficult to compare these data, however, to those of the present experiment since Kintsch (1965) presented averages of 14 sessions, and these 14 sessions followed only 7 sessions of exposure to the VI 40-s schedule. The rats had been previously exposed to the VR 15 schedule. Under VR, Kintsch (1965) found that average IRT duration decreased for the first 4-5 responses for both rats. Following this decrease average IRT increased for 1 rat and remained unchanged for the other. These data are, thus, somewhat more consistent with the findings for Experiments 1 and 2 with regards to interlocking/ratio conditions.

Fsiya (1932) also presented data relevant to changes in IRT duration but his data are difficult to compare with the present data. He showed IRT duration as a function of time

since reinforcement but plotted 30,000 IRTs in each figure and it is, thus, difficult to tell whether apparent changes were due to changes in the probability of different IRTs or to the dwindling number of IRTs occurring at a larger temporal distance from reinforcement. Perhaps the most comparable figures that Palya (1992) presented are those for local rates of response as a function of time since reinforcement. Under VI there was an initial, large increase in rate of response over the first few seconds, which probably corresponds to the averaging of responding and pauses. After this, response rate rose from about 1.0 responses/s to about 1.2 responses/s over 90 s. This pigeon's data are, therefore, mostly inconsistent with the general increase in average IRT duration in Experiment 1. Under VR, there was the same increase in rate of response over the first few seconds, followed by a slight (a few tenths of a response per second) reduction over about the next 10-15 s. After this point rate of response was essentially steady over the next 70-s. These data are somewhat more consistent with the data reported here for interlock/ratio schedules in Experiments 1 and 2. That is, after the postreinforcement pause, the average IRT duration (1/response rate) tended to be the shortest and then to increase slightly. There were, of course, considerable differences between the present experiments and those of Kintsch (1965) and Palya (1992). Although Palya (1992) utilized a VI 60-s schedule, the distribution was

exponential as opposed to the constant probability schedule used in Experiment 1. Kintsch utilized a VI 40 s with a rectangular distribution of values. The VR schedule used by Pelya required many more responses (150) per reinforcer than occurred under any interlock/ratio schedule. The largest VR schedule used in Experiment 1 was 61. Kintsch used a VR 15.

There were, for many of the pigeons, changes in responding that occurred reliably within a session. Perhaps the most complex changes were exhibited by Pigeon 1097 under VI 60 s (Figure 28, left column). There was, for this Pigeon under VI 60 s, a systematic change in longer IRTs that were, apparently, not part of the 0.3-s rhythm. The longest IRTs tended to occur at the beginning of the session, and the length of these IRTs tended to decrease across the session. For this pigeon there were also periods during which IRTs around 0.3 s were relatively rare and these periods tended not to occur until after about 500 responses had been emitted. For Pigeon 5994 under VI (Figure 29, left column), there was, in general, a slight deterioration in "accuracy" across the session. In particular, the band at about 1.0 s (i.e., two "misses") tended to become more distinct near the end of the session. There was also some tendency for long IRTs to be less probable at the beginning of the session. For Pigeon 2760 under VI 60 s (Figure 30), responding also tended to be more "accurate" at the beginning of the session, though this pigeon's "accuracy" was poor throughout the session. Under

VR for Pigeon 1097 (Figure 28, right column), there was some slight tendency for long IRTs (greater than about 2.0 s) to be absent for about the first 500 to 1000 responses. For Pigeon 5994 under VR (Figure 29, right column) there was a clear progressive change in "accuracy" across the session. The "accuracy" deteriorated and this was accompanied by an increase in the probability of longer IRTs which were not part of a discernable rhythm. In Experiment 2, Pigeons 1694 and 3673 (Figure 38) also showed changes in responding within a session during conditions where MTE<0. For Pigeon 1694, IRTs longer than 1.0 s were virtually absent for the first 500 responses. For Pigeon 3673 there was some tendency for "accuracy" to deteriorate across the session and for the probability and length of long IRTs to increase. Pigeon 1404 did not show any appreciable change within a session under these conditions. Under VT, responding changed within sessions to a considerable extent for the two pigeons (1694 and 1404) that continued to respond. The changes are best seen in the cumulative records presented in Figure 36. For Pigeon 1694, there were periods during which responding did not occur or was at a very low rate. These could occur at any time during the session, though typically they did not occur at the beginning of the session. For Pigeon 1404 responding typically occurred at a very low rate during the first half of the session. During the second half of the session periods of rather high-rate responding were punctuated by periods of nonresponding.

In addition to IRT distributions and the "dot-plots" (IRT duration as a function of position in the session) the IRT/OP functions were analyzed for the stable-state conditions. (These data, along with reinforced IRTS and delays to reinforcement, were not presented for the transitions in an effort to keep the amount of data presented at least somewhat manageable.) The location of the modes in the IRT/OP functions were predictable from the IRT distributions, but the height of the modes were not necessarily predictable on that basis. In Experiment 1 under VI, for Pigeons 1097 and 5994, the height of the modes representing the 0.3-s rhythm tended to increase as a function of the IRT duration. Even where the fundamental at about 0.3 s was the highest in the IRT distribution (Pigeon 5994) it was not the highest in the IRT/OP function. In contrast, under interlocking/ratio schedules the mode at about 0.3 s tended to be the highest in the IRT/OP function and the IRT distribution. For Pigeon 2760 the IRT/OP function tended to increase sharply at about 1.2 s under both VI and interlocking/ratio schedules. In Experiment 2, the IRT/OP functions for Pigeons 1694 and 3673 under VT 600 s, RTF=-15.0 s were similar to those for Pigeons 1097 and 5994 under interlocking/ratio conditions. For Pigeon 1404 the IRT/OP function decreased up to about 1.0 s. Recall that this pigeon had a somewhat unique pattern of responding in that it did not show much responding at the 0.3 s rhythm. For Pigeons 1694 and 1404 under VT, the

highest early mode was at about 0.14 s representing the most rapid rhythm. After this, the function was rather flat.

There are few data with which the IRT/OP functions may be meaningfully compared. It is difficult to find IRT distributions and IRT/OP functions where the class-interval size is small enough to capture the nuances described in the present studies, and it is difficult to find any IRT/OP functions under VR or RR schedules. Shimp (1967) exposed Pigeons to a VI 60-s schedule and plotted IRT/OP functions using a class-interval size of 0.3 s. For 2 of the 3 pigeons there was a peak in the function at about 0.6 s and for the third pigeon there was a peak at about 0.9 s. For the two pigeons that showed a peak in the IRT/OP function at about 0.6 s there was a second peak at about 2.1 to 2.4 s. Although the two data sets are difficult to compare because of the difference in class-interval size (Ray & McGill, 1964), the data presented by Shimp (1967) are, for the most part, consistent with the IRT/OP functions presented here. If the data from VI 60 s in Experiment 1 were replotted using a larger class-interval size (Shimp used 0.3 s) and the analysis carried out further (Shimp's 'dump bin' was greater than 11.0 s) 2 of the 3 subjects (Pigeons 1057 and 5994) would probably show a bimodal function similar to Shimp's and the third (Pigeon 2760) would show a unimodal function with a peak at about 1.2-1.5 s. Kintsch (1965; see above), using rats and 0.5-s bins, also plotted IRT/OP functions for both VI and VR. Under VI, for one rat, the

function had an initial peak at about 1.0-1.5 s and then declined thereafter, though there appeared to be some smaller additional peaks. For the second rat, there was also a peak at about 1.0-1.5 s, but there were also peaks at about 2.0 and 3.0 s, in addition to some other smaller peaks superimposed on the general decline. Under VR, the function for both rats peaked at 0.5 s and declined thereafter. These data are comparable to the present data in that the peak under VR was to the left of that for VI.

Molecular Data: Transitions

For the most part, the molecular data during transitions from both experiments can be similarly characterized. In general, rhythmic responding tended to be affected by a change in conditions at the same rate as nonrhythmic responding. Where response rate increased, rhythmic responding came to predominate and "accuracy" improved. Where response rates decreased, nonrhythmic responding increased in probability as rhythmic responding and "accuracy" declined. In addition to the above characterizations, it was also true that most of the changes tended to occur between sessions.

There were a couple of aspects of responding during some transitions that were especially worth note. For Pigeons 1097 and 2760 (Experiment 1), during the first few sessions following the change back to VI, response patterning within sessions was somewhat disorderly. That is, there were portions of the session during which response

patterning like that during VI would suddenly intrude. For the most part, the response patterning during these early sessions was like that during interlock/ratio schedules (for Pigeon 276D the transition in question occurred following the condition in which RTE was an inverse function of responding) except for the sudden intrusion of VI-like response patterning. Pigeon 140A (Experiment 2), surprisingly, briefly displayed responding at the 0.3 to 0.4-s rhythm during the return to VT (after responding was eliminated during the condition in which responses added time to the currently scheduled interval). This was surprising since this pigeon had shown little or no responding of this type under any stable state. By the sixth session following the change back to VT, the response pattern was again characterized by short-duration IRTs.

The fact that, during the return to VI 60 s, Pigeons 109T and 276D showed brief intrusions of VI-like responding represents, to some extent, a violation of the general rule that changes during transitions tend to be greatest between sessions. During these kinds of schedule changes, rate of reinforcement changed immediately upon reintroduction of the VI 60 s schedule, independent of changes in rate of response. Perhaps dramatic within-session changes occur only when rate of reinforcement is reduced immediately upon a change in schedules. Some support for this notion comes from Pigeon 367J in Experiment 2 when the VT 21 1-s schedule was changed back to VT 300 s with RTE=-7.2 s. Recall that,

for this pigeon, responding was eliminated under the VT schedule. Reintroduction of the VT 300 s with RTE=-7.2 s thus produced a large decrease in rate of reinforcement. During the third session, responding began after a considerable amount of time had passed from the beginning of the session (responding remained essentially zero during the first two sessions). Once responding had begun, it was essentially indistinguishable from responding originally maintained by this schedule. This represents, thus, a rather dramatic within-session change.

It is not clear why Pigeon 1404 would show transient responding at the 0.3-s rhythm. Although this pigeon never showed this response pattern under stable conditions or during any transition other than the one described above, it did show such response patterns before response rate stabilized under the first condition (VT 600 s with RTE=-15.0 s). Indeed, early in the experiment, Pigeon 1404 did not show any responding at the 0.14-s rhythm. Instead, this pigeon's response pattern was characterized by a broad band centered at about 0.35 s and a second band centered at about 0.70 s.

The Future of Schedule-Space Research

A variety of experiments are suggested by the previous discussion. Of primary importance is the more complete determination of the shape of the surface which results when rate of response is plotted as a function of BI, RTE, and s. It was suggested that the general function which describes

this surface would constitute a law which would be important in-and-of itself, but also as a starting point for the determination of laws involving controlling variables which would constitute the elements in a system of differential or difference equations. Of particular interest is the determination of the continuity of the surface. Are there some regions in which there are no stable-states? Is there hysteresis in these regions? The answers to these questions will constrain the kind of system of differential equations applicable and the general way in which the system is conceptualized.

Another set of important experiments would involve the determination of how response rate changes, through time, as a function of moving from one part of the schedule space to another. Experiment 1 represents a preliminary attempt where motion in the schedule space was constrained by the stipulation that rate of reinforcement could not change simply as a function of changing the schedules.

The schedule space should prove a rich source of pharmacological experiments. Interval and ratio schedules, for example, generate different patterns of behavior, and responding under control of interval and ratio schedules is differentially affected by the acute administration of some drugs (Gonzales & Goldberg, 1977; Kelleher & Morse, 1965). Further, the extent to which tolerance develops to the effects of cocaine depend on fixed-ratio parameter (Hoffman, Branch, & Sizemore, 1976; Hughes & Branch, 1991) but not on

the fixed-interval parameter (Schoma & Brench, 1989) The manipulation of interlocking schedules, therefore, must almost certainly represent a powerful way systematically to modulate drug-effects, since this represents a systematic manipulation of the interval-ratio continuum. Further, it is clear from the interlocking-schedule data that behavioral states intermediate to those under interval and ratio schedules can be maintained. It would, thus, seem to be of interest to obtain dose-effect curves under different schedule parameters. The effects of drugs on behavioral states intermediate to those produced by ratio and interval schedules would be of particular interest. It would also be of interest to study the effects of drugs on responding maintained by different schedule parameters that produce, nevertheless, essentially identical rates and patterns of response. Should there be a difference in the dose-effect curves under the different parameters they would have to be due to variables that do not differentiate responding during baseline. It would be equally interesting if there were no differences in the dose-effect curves for this would begin to delimit the boundaries of the schedule-dependent drug effect.

There are several ways to investigate the effects of drugs on behavior maintained by schedules in the interval-ratio continuum. One set of parameters might be in effect for a long period of time and dose-effect curves obtained for each set of parameters or several different sets could

be examined simultaneously in the context of a multiple schedule. A particularly interesting way to utilize interlocking schedules to investigate drug effects would be to maintain responding under one set of parameters but have probe sessions where the parameters were different. The parameters for the probe session could be selected so as to produce the same rate of reinforcement given no change in rate of response. No matter what parameters are used, it is unlikely that the probe sessions themselves would have any behavioral effect, given they are separated by enough baseline sessions (though, this is an interesting behavioral question in and of itself). Drugs would be administered during some baseline sessions and during some probe sessions eventually yielding dose-effect functions at different schedule parameters. This somewhat unorthodox experiment is designed to investigate the role of the dynamic relation between behavior and environment in influencing drug effects. What is arranged during probe sessions are different dynamic relations between response rates, reinforcement rates, and number of responses per reinforcer (at least, at the molar level of description). All drug experiments introduce the issue of this dynamic relation because drug administration usually affects responding and an understanding of the role of these temporary dynamic changes is basic to behavioral pharmacology (Branch, 1984). The experiment is unorthodox because the probe sessions involve both schedule changes and drug administration.

Another interesting set of experiments would involve comparisons of positive and negative reinforcement. Before these are described, however, some preliminary discussion is required.

It is generally accepted that the terms "positive" and "negative" refer, in part, to the properties of an experimental arrangement. That is, positive reinforcement involves operations which arrange for a positive correlation between responding and consequences, and negative reinforcement involves operations which arrange for a negative correlation. If the former arrangements result in an increase in rate of response (or maintenance of responding) the *process* of positive reinforcement is said to have been observed and if the latter arrangements result in an increase in rate of response (or response maintenance) the process observed is said to be negative reinforcement. (Positive and negative punishment are similarly defined except the direction of the effect on behavior is a decrease.)

In the definitions presented above, there is no mention of the temporal relationship between responding and consequences. Traditionally, positive reinforcement has been arranged by making some response *temporally* contiguous with an event. When this is the case, a correlation is also arranged, but it is a special kind of correlation because there is the added stipulation of temporal contiguity. There is a sense in which operations reflecting definitions

based strictly on correlation are the most fundamental; a correlation may be arranged without assuming temporal contiguity, but the reverse is not true. (Notice that it is not being claimed that, at the controlling variable level, there is no relationship between the arranged correlation and the temporal distance between responses and reinforcers or that temporal distance per se is not "really" the operative variable.) As long as operations are important in the definitions of basic behavioral processes, such as positive and negative reinforcement, it is probably best to keep correlation *per se* and correlations produced by arranging temporal contiguity operationally separate. The former is the more general from the standpoint of experimental operations.

The foregoing discussion points out why the schedule space offered here is referred to as the *fundamental* schedule space; it is built up from the general notion of response-dependency or correlation. The special kind of correlation which is arranged when reinforcers are made necessarily temporally contiguous is "factored in" by arranging a tandem requirement defined by the s parameter.

The operational separation of correlation and contiguity eliminates an asymmetry between positive and negative reinforcement procedures that has been described as necessary. Hinslie (1934), for example, wrote: "There is a fundamental asymmetry, [between positive and negative reinforcement] for if a stimulus or situation is to be

reducible or removable by some response, that response must occur in its presence. In contrast, positively reinforced responses necessarily occur in the absence of stimuli upon which reinforcement is based." Catania (1973) suggested that this asymmetry might be a basis to distinguish positive and negative reinforcement. The asymmetry is not, however, necessary and its elimination within the schedule space suggests further its fundamental nature.

When s=0, there exists a symmetry among schedules where the absolute value of RTE is the same but the sign is different. In such schedules the slope of the feedback functions are the same except in sign. The y-intercept is equal when BI is the same under both schedules. Where BI is different, they are still of the same slope, but have different y-intercepts. The two possibilities are depicted in Figure 78 which shows feedback functions from two schedules in each panel. One of the schedules in each panel arranges a positive correlation between responding and consequence, while the other arranges a negative correlation. In the top panel, the two schedules have equal BI values, and in the bottom panel they do not.

This symmetry of operation suggests some experiments. Of primary importance is the determination of empirical laws relevant to the fundamental positive and negative reinforcement schedules (i.e., where s=0). Preliminary experimentation should involve experiments such like Experiments 1 and 2 but, of course, utilizing some aversive

consequence and primarily positive values of RTE (but, as in Experiment 1, it might be necessary to change the sign of RTE in order to eliminate responding in some subjects).

Other experiments might directly compare symmetrical schedules within subjects. For example, response rates could be equated (probably by manipulation of shock intensity) under symmetrical schedules as shown in the top panel of Figure 78. Given that rates of response can be equated, the effects of changing the schedules to other equi-slope schedules could then be examined. The feedback functions of the new schedules could have the same y-intercept but it would also be of interest to examine changes where the feedback functions for the new schedules intersect the old ones at the point corresponding to the rate of responding maintained by both schedules. Of primary concern here is the extent of the symmetry in performance when the operations are changed in a symmetrical fashion.

Molecularism, Molarism, Controlling Variables, and the Independent Variable Approach

The position taken in this paper could be characterized as "atheoretical," especially in relation to the views frequently referred to as "molecular" and "molar." An interpretation of much of the data, from the standpoint of "molarism" and "molecularism," will be offered below after the distinctions between them and the independent-variable approach are clarified.

Figure 7B. Feedback functions for two kinds of symmetrical schedules. In the top panel, BI is equal for both schedules and, in the bottom panel it is not. X-axes: rate of response. Y-axes: rate of reinforcement.

Rate of Reinforcement
Rate of Response

The "independent variable" approach is the most straightforward--independent variables are independent of the subject's behavior. That is, independent variables are what the experimenter arranges. Rate of reinforcement, for example, is never an independent variable in schedules in which the occurrence of reinforcement depends, in any way, on a subject's behavior since if the subject never responded, reinforcement would occur at a different rate than if responding did occur. Maximum possible rate of reinforcement, on the other hand, could be an independent variable.

The meaning of the term "molecularism," on the other hand, is somewhat ambiguous. Baum (1989), for example, defined "molecular" variables as those that "can be measured on any occurrence of an event." Later he wrote "The standard molecular account of the interval-ratio rate difference appeals to two factors, the strengthening effect of reinforcement on the response immediately preceding it and the differential reinforcement of inter-response times." The ambiguity of the term "molecularism" is evident in the juxtaposition of these two statements. If one holds that interval-ratio response-rate differences, for example, depend on the average reinforced IRTs, or rate of reinforcement for particular classes of IRTs (Anger, 1973), or the difference between the distribution of all IRTs and the distribution of reinforced IRTs, is one expressing a molecular view? The phrases "average IRT," "rate at which a

particular class of IRTs is reinforced," and "distribution of IRTs," all imply measurement across time. A similar argument could be made with respect to the effects of delays imposed between reinforcers and the responses upon which they are dependent. Suppose one argued that the extent of rate reductions is related to the mean obtained delay between responses and reinforcers--would such an argument be molecular? Baum (1989) implied that molecularism must be built around the notion that each reinforcer must change something akin to a state of the organism. This seems not to be in keeping with usage of "molecularism" in much of the experimental analysis of behavior. In light of the above discussion, it would seem better to define "molecularism" as an explanation of schedule effects that relies primarily on instantaneous or aggregate effects of the temporal distance between certain responses and reinforcers.

The term "molarism," too, is characterized by a certain amount of ambiguity for reasons similar to those pertaining to "molecularism." If molarism is defined simply by the fact that measurement takes place over time, then IRT distributions, average IRT, and so forth, would be "molar" variables. It would seem to be more in the spirit of common usage to define molarism as the view that schedule-controlled behavior can primarily be understood in terms of aspects of feedback functions.

Both molecular and molar approaches are "controlling-variable" approaches. That is, it is commonly recognized

that behavior is controlled by such variables, but also that the level of these variables can depend on behavior. Baum (1989), for example, wrote "In a feedback system the distinction between independent and dependent variables becomes arbitrary; strictly speaking, all variables depend on one another." It was argued here (Introduction) that a quantitative treatment of schedule-controlled behavior based on controlling-variables must rely on the hypothetico-deductive method. This is in contrast to Baum's (1989) assertion that only molecularism requires "hypothetical constructs."

Combinations of Molecular and Molar Explanations

Although "molecular" and "molar" explanations are frequently regarded as mutually exclusive (Baum, 1973, 1989) they need not be so regarded. Indeed, the widespread practice of controlling rate of reinforcement, even among researchers regarded as "molecularists," suggests that a hybrid of "molecularism" and "molarism" is common. Further, Anger's (1973) position (described above) seemed to have been that performance under VI schedules is the result of the rate of reinforcement for various IRTs. Such a position suggests that molarism and molecularism are completely inextricable from each other.

Molecular Interpretations of the Results

Most of the data presented here can be accommodated, to some extent, by a molecular framework. Molecular analyses of inter-interval differences typically rely on the argument

that interval schedules generally control lower rates of responses because interval schedules lead to the differential reinforcement of relatively longer IRTs (Anger, 1956; Morse, 1966). That is, the probability that a reinforcer has been "set up" increases as a function of time. The longer the IRT, therefore, the higher the probability that reinforcement has been "set-up." Under ratio schedules, this is not the case. Some researchers have asserted, further, that ratio schedules differentially reinforce short IRTs. Sometimes this notion is combined with long-IRT reinforcement in interval schedules (Morse, 1966) to explain ratio-interval response-rate differences or is itself the primary molecular component of the explanation (Ferster & Skinner, 1957). Schedules that are more like ratio-schedules should, according to all of these interpretations, produce higher rates of response than interval-schedules. Rider (1977), however, has suggested that molecular theories are somewhat ambiguous as to their predictions concerning interlocking interval- and ratio- schedules because they combine the contingencies from both. He does, however, concede that molecular analysis could, therefore, predict rates of response intermediate to those found under interval and ratio schedules--exactly what he found (see Introduction). Although, rates of response intermediate to ratio- and interval-schedules were observed in Experiment 1 (albeit only for Pigeon 5994) and in other experiments it is also common for some interlocking-schedules to produce the

same rates of response as ratio schedules. It is not clear how this fact relates to the molecular perspective, but it is doubtful that it provides anything like a disconfirmation. Indeed, it is not clear that molecular explanations are sufficiently precise to be easily disconfirmed. It could be argued that since, in interlocking-schedules, there is always the potential for reinforcement of long IRTs, they should always control rates of response intermediate to ratio- and interval-schedules. Molecular theories, however, do not themselves typically specify potential rate-limiting characteristics of schedules. Once some threshold is exceeded, rates of response could be driven to some maximum determined by other features of the schedule or organism.

The data from Experiment 2, as well as a variety experiments examining the effects of response-independent reinforcement, are also accommodated by a molecular perspective. Recall that response rate typically declines when a schedule is changed from one in which reinforcement depends in some way upon responding to one in which it does not. Response-independent schedules allow for reinforcement to occur at some temporal distance from responses and responding is, thus, "weakened" (or other responses contiguous with reinforcement are "strengthened"). Once responding becomes less frequent, it becomes even more likely that reinforcement will occur at a temporal distance from responses, causing responding to become even less

frequent etc. The data from experiment 2 support this view; the two pigeons that showed many IRTs at 0.14 s (Pigeons 1694 and 1404) continued to respond under VT, albeit at a rate lower than under the previous condition in which rate of reinforcement was a function of rate of responding. The occurrence of such short IRTs makes it less likely that reinforcement will occur at a considerable temporal distance from responses. For these two pigeons responding was eliminated when responses added time to the currently scheduled interval, thereby assuring that every food delivery would be preceded by a pause.

Some other features of the results from Experiment 2 are difficult to account for based simply on the temporal distance between responses and reinforcement. For Pigeons 1694 and 1404, response rate increased when the VT schedule was reinstated following the condition where MTE>0, despite the fact that responding had been eliminated under the latter condition. Similarly, for Pigeon 3673, rate of responding increased when VT 300 s with MTE=-0.72 s was reinstated even though responding had been eliminated under VT. Recall that these schedule changes produced an immediate change in rate of reinforcement. Specifically, rate of reinforcement decreased. There are other processes which may account for these findings. All three subjects had originally been trained by "the method of successive approximations". During training low rates of reinforcement were associated with a shift in contingencies in which

approximations of keypecking, and eventually, keypecking itself, was subsequently reinforced, resulting in a dramatic increase in rate of reinforcement. Thus, a decrease in rate of reinforcement could discriminatively control pecking. Further, a decrease in rate of reinforcement or the cessation of reinforcement, may generate responses that were at one time reinforced

It is difficult to discuss the data from the transitions in relation to either molecular or molar perspectives because these perspectives rarely generate hypotheses of a quantitative nature. This is especially true with respect to changes in responding over time. Catania (1984, p 167), however, has asserted that the "rapid separation" of rates of response on VI-yoked-VR, and VR-yoked-VI (Catania, Matthews, Silverman, & Yohalem, 1977; Ferster & Skinner, 1957) procedures is inconsistent with a strictly molecular viewpoint, given the length of time that it takes responding to come under control of IRT>t schedules. His argument seems to be that the separation of rates of response in such experiments depends on the differential reinforcement of long-IRTs for the subject exposed to the interval-schedule For two of the three subjects in Experiment 1, rate of response increased rather slowly when the schedule was changed from VI 60 s to interlocking/ratio schedules. This manipulation, however, would represent a "release" from differential long-IRT reinforcement. This still would constitute the

reinforcement of different classes of IRTs, or at least a different average reinforced IRT and, hence, from Catania's (1984) point of view, could be thought of as supporting a molecular viewpoint. On the other hand, for all three pigeons in Experiment 1, the return to VI 60 s produced quite rapid changes in response rate. This finding appears inconsistent with respect to a strictly molecular point of view. It is true that rate of reinforcement decreased when the schedule was changed from interlocking/ratio to VI 60 s, but to argue that this variable was important is to depart from a strictly molecular view. Further, it is not true that all IRT- differentiation procedures produce relatively slow transitions. For example, Kuch and Platt (1976), using a percentile-schedule (a schedule in which the criterion for reinforcement is based on the organism's recently emitted IRTs; see Allenas and Platt, 1973) in which rate of reinforcement remained essentially constant throughout the experiment, observed rather rapid transitions, especially when long-IRTs were reinforced. Where short-IRTs were reinforced, the effects on response rate were small, but these occurred within 20 hours. This latter finding corresponds well with the data from Experiment 1; two of the three subjects typically showed small increases in rate of response during the first thirty sessions. The rapid, large decreases obtained in Experiment 1 upon change from ratio/interlocking-schedules to VI 60 s, are also consistent with the findings of Kuch and Platt (1976).

Molar Interpretations of the Results

There is a close connection between the "independent variables" approach and molar approaches. Although the independent variable approach stresses a purely descriptive endeavor based on the experimenter's arrangements, it is convenient to portray these arrangements graphically in terms of their feedback functions; no matter what one's orientation, the study of operant behavior must somehow involve the effect of responses on the temporal locus of consequences. This relationship between responding and consequences is captured by "theoretical feedback functions." If molarism is viewed as a position which is concerned with the relationship between theoretical feedback functions and responding, there is little difference between molarism and the independent-variable approach; the nature of the theoretical feedback functions are given mathematically by the independent-variables. The advantage of feedback functions is, however, that predictions may be made as to the effects of other independent variables based on their associated feedback functions. This seems to be, in fact, the way that feedback functions have been used. In the Introduction it was stated that feedback functions (or their derivatives) could constitute an element of a system of differential or difference equations. In such a system, the feedback function would have a different meaning; it would no longer be "permissible" to make statements based on the form of the *entire* feedback function. The only

"acceptable" quantities would be those that are actually experienced by the organism. This may seem confusing given that theoretical feedback functions should predict the quantities that are actually experienced by the organism. It is, however, depending on the "temporal window" over which the molar quantities are calculated, possible that portions of the theoretical feedback functions that enter into molar theories of performance are not experienced by the organism. For example, if rates of reinforcement and response are calculated over 2-minute intervals under a VI 120-s schedule, most of the quantities obtained would lie along the asymptote of the feedback function, yet the theoretical feedback functions for VI schedules contain a portion (at very low rates of response) that is equal to that of an FR 1. It is unlikely that rates of response averaged over, for example, two minute periods would be low enough for this portion of the function to be experienced.

If molarism is seen as an attempt to predict the effects of schedules based on their theoretical feedback functions, then the data from Experiments 1, 2, and related experiments are, with some reservations, consistent with the molar view based on ratio-interval differences. The first derivative of an interlocking-schedule feedback function, like that for a ratio schedule, does not approach zero as does the derivative of an interval schedule. Ratio and interlocking schedules produced similar rates in Experiment 1. Further, although rate of response tends eventually to

decrease as ratio value increases (i.e., the derivative of the associated feedback function decreases), a wide range of ratio schedules produce nearly the same high rate of response. In Experiment 1, rates of response under various interlocking schedules tended to be equivalent and equal to that of the ratio schedules. Arguments based on feedback functions, too, have been advanced to explain the decreases in rate of response produced by response-independent reinforcement on behavior previously maintained by response-dependent reinforcement. From this perspective, there are two ways that transitions from response-dependent to response-independent reinforcement could produce decreases in rate of response; the slope of the feedback function is zero everywhere, and the variance in the feedback data (points in the response rate/reinforcement rate space) should be greater under response-independent schedules than response-dependent schedules. The range of the feedback data would, in any event, almost certainly be greater in response-independent schedules.

Both of the above interpretations are potentially troublesome for molarism. If the difference between VT and VI schedules is a matter of the slope of the feedback function at asymptote, then one would expect that slight changes in the derivative at asymptote under other schedule pairs would be a powerful variable. It is almost certain, however, that changing from a VI schedule to an interlocking schedule that is very close to a VI schedule (i.e., RTM is

close to zero) would produce little or no change in response rate despite a change in the slope of the asymptote comparable to that which occurs when a schedule is changed from VI to VT. On the other hand, if the "variance argument" is accepted then one is almost compelled to argue that the appropriate temporal "window" for response and reinforcement rate calculations is quite short. If a VI schedule is changed to a VT schedule matched to rate of reinforcement the first few sessions following this change would contain as many responses and reinforcers as under the preceding VI. Certainly, then, some kind of whole-session aggregation would be insufficient to explain the initial decrease in response rate. Even in rather short periods of time there would tend to be as many responses and reinforcers as under the VI.

The Falsifiability of Molar and Molecular Positions

It is not clear that there are experiments that are uninterpretable from either a molar or molecular position and, despite considerable attention to the issue by behavior analysts for nearly 25 years, both positions seem to possess committed proponents. Experiments, such as Experiment 2, which directly manipulate only the dependency between responses and consequences, must also arrange indirect relationships between the temporal locus of responses and consequences. Similiarly, experiments designed to "disprove" molar interpretations cannot do so because molar relationships will always be present. This includes

experiments which show changes in behavior despite the fact that overall rate of reinforcement remains roughly constant over the entire course of the experiment (Galbicka, Kautz, & Jegers, 1993; Kuch & Platt, 1976). These experiments typically arrange reinforcement based on characteristics of an organism's recently emitted behavior, and contingencies, therefore, change as behavior changes. It is this aspect of such experiments which allows rate of reinforcement to remain constant (in much the same way as pressure may be held constant in thermodynamic experiments, despite changes in temperature, by allowing volume to vary). It is likely, however, that such experiments can be described in terms of "temporally-local feedback functions" and their relationship to responding. If, for example, only the longest IRTs of an organism's temporally-local distribution of IRTs are listed for reinforcement, then higher than average rates of responding will result in a locally low rate of reinforcement, whereas a local low rate of responding will result in a locally high rate of reinforcement.

Molecularists have, perhaps, been guilty of setting up a "strawman" in their attacks on molarism. Frequently, as has been pointed out, molecularists' arguments against molarism focus on rate of reinforcement, whereas--even if this has not been made clear--much of the molarists' argument rests on the derivative of the feedback function.

Ultimately, molecular and molar theories must make quantitative predictions of performance during transitions

and stable-states. Such an endeavor, if related to mainstream controlling-variable approaches, must respect the implications of the controlling variable approach, i.e., that responding under schedules of reinforcement is describable by something like a system of coupled differential equations. This raises the final topic to be considered.

Differential equations are relevant only to continuous variables. It was pointed out earlier that response rate, the most widely used dependent variable in the experimental analysis of behavior, has the dimensions cycles/time. Because "cycle" may take only integer values, response rate cannot easily be regarded as a continuous variable. One solution to this problem seems to be that rate of response may be regarded as a measure of "strength" of responding. This conception is not, however, without its problems. Foremost among these is the differentiability of response rate itself. As Marr (1979) has asked, which shows greater response strength, responding maintained under a VI schedule, or responding maintained under a VI schedule with a tandem short-IRT requirement? A simple conception of rate as a measure of *strength* appears inadequate. Less troublesome, perhaps, is the notion of *probability* of response, a quantity that, like *strength*, is itself not directly observable. Unlike strength, however, probability seems much less controversial; there is no problem in identifying a higher rate of response with a higher

probability of responding. It seems likely, therefore, that the quantities entering into differential equations will be probabilities which may, nonetheless, be expressed in terms of observed rates. This solution may not prove to be, ultimately, satisfactory to all scientists involved in the experimental analysis of behavior; some may be uncomfortable with the notion of probability playing a fundamental role, since this seems to introduce some degree of randomness at a fundamental level. That is, the probabilities may be determined, but not the actual emission of responses. This is, however, more an argument against the conception of operant behavior as spontaneous and emitted, rather than an argument against a mathematical treatment which simply accepts these aspects of operant behavior. It is possible that, eventually, we will dispense with these probabilistic aspects of operant behavior. Perhaps a treatment of behavior will, ultimately, involve a treatment of the continuous spatial locus of the organism or its parts through time and, thus be analysed in strictly deterministic terms. In closing, it should be added that schedule-controlled behavior may be more amenable to description in terms of discrete mathematical systems, i.e., in terms of difference equations. Each occurrence of an unreinforced response may lower the probability of responding and each reinforced response may increase the probability. This would, of course, form only the core of a mathematical

description. This kind of description, however, brings to mind difference, rather than differential equations.

CHAPTER 5

CONCLUSIONS

A 3-parameter schedule space (the *fundamental* schedule space), within which are located several different schedules of reinforcement, was described. In addition to time, interval, and ratio schedules, the space contains schedules which represent a continuum encompassing interlocking time-ratio and interval-ratio schedules, as well as DRL-like schedules, schedules of event postponement, continuously present "events," and extinction. The basic *interevent interval (EI)*, when considered in isolation is simply a time schedule. Responses may, however, as determined by the *response-time exchange value (RTE)*, add time to, or subtract time from, the interval currently arranged by *EI*. The parameter, *s*, controls the amount of time--after an event is scheduled to occur on the basis of the former two parameters--for the event to actually occur. If, however, a response occurs during this time the event occurs immediately. *EI* and *RTE*, considered in isolation, arrange a continuum of dependency, whereas *EI* and *s* arrange a continuum encompassing response-independent events (no necessary temporal relation between responding and events) and events which must be temporally contiguous with responses.

Parametric manipulation of this space should provide a sort of empirical integration of many schedules of positive reinforcement, since the stable-state behavior controlled within such a space can, presumably, be described by an algebraic equation in 3 variables--the 3 parameters of the space. This endeavor was referred to as the "independent variable approach" to the systematization of schedule-controlled behavior, and contrasted with the "controlling-variable approach" (Zeiler, 1977). According to the controlling-variable approach, the levels of variables thought to be relevant to behavior may, themselves, be functions of responding, i.e., not independent variables. It was suggested that the "controlling-variable approach" implies that schedule-controlled behavior can be understood in terms of a system of coupled differential or difference equations. It was pointed out that these two approaches are not, ultimately, contradictory; as Ferster and Skinner (1957) have said, the functions obtained by parametric manipulation of schedules provide the facts to be explained in terms of controlling variables.

In addition to the "fundamental schedule space," other schedule spaces were considered in terms of their procedures, theoretical feedback functions, and the data generated.

In the research presented here, pigeons were exposed to schedules from one of two cross-sections of the space. The cross-sections, in traditional terminology, corresponded to

interlocking interval-ratio and interlocking time-ratio schedules. For the most part, RTE was either negative (responses subtracted time off of the scheduled interval) or zero (responses did not affect the scheduled interval). The schedules investigated in both experiments fell roughly along a line oriented diagonally through the cross-section; that is, larger RI values were associated with smaller (more negative) RTE values. Pigeons in Experiment 1 (a-->infinity) were always exposed to the original baseline VI 60 a schedule (RI=60, RTE=0) following each exposure to other schedules. In Experiment 2 (a=0) pigeons were exposed to a series of schedules in which food delivery was increasingly less dependent on responding, and then exposed to the same schedules in reverse order.

The goal of the experiments reported here was, simply, to characterize responding maintained by schedules in the space in detail. In addition to overall rate of response during stable states and transitions, the "fine structure" of responding was analyzed in terms of IRT distributions, IRTS/OP, delays between responses and food (Experiment 2) and sequences of IRTS.

In both experiments, the maximum rate of response first increased rapidly as RI was increased and RTE was decreased. After a certain point, however, rate of response no longer increased. These data, along with those from the few other studies of interlocking schedules, suggest that response rate is some monotonically increasing, s-shaped function

of ~RTF when SI is held constant. An algebraic expression was offered as a possible description of the spaces for values of RTF<0. In some cases where s-->0 (time and interlocking time-ratio schedules) the curve may be shifted somewhat so that values of RTF>0 must be considered. The possibility that some portions of the space could show discontinuities was considered and the possible relevance of Catastrophe Theory (Thom, 1975) was discussed. Under most circumstances, especially where the schedule in effect became similar to ratio schedules, response rate appeared to oscillate in an sporadic fashion. It was suggested, based on these data and those from some other experiments, that this type of oscillation may not be typical.

Analysis of the fine structure of responding under stable states revealed that, for the most part, the pigeons pecked at about 3-4 responses per second. This was seen most clearly by examining plots of IRT duration as a function of ordinal position in the session. Such plots showed a distinct band at about 0.25 to 0.35 s, and typically at integral multiples thereof. The bands located at integral multiples, it was argued, probably resulted from pecks that did not contact the key or were of insufficient force to close the microswitch. Although all of the pigeons in Experiment 1 responded at the typical rhythm, there were many fewer "misses" under interlocking and ratio schedules than under the baseline interval schedule. There were, during the baseline interval schedule, many more IRTS that

were not part of the fundamental rhythm or its harmonics. For most of the pigeons, "misses," and the occurrence of long IRTS, grew slightly more probable as a function of ordinal position, measured from the occurrence of food.

Transitions between different schedules within the space were frequently rapid. During some schedule changes, rate of reinforcement was held constant at the time of transition; that is, parameter values were chosen such that, if rate of response did not change, rate of reinforcement did not change. Under these conditions rate of response sometimes changed rather slowly across sessions. In contrast, schedule changes that involved an immediate change in rate of reinforcement were always relatively rapid. During schedule changes where rate of reinforcement did not change until rate of response changed, there was little change in rate of response within a session. This was true even if the overall response rate was changing quite rapidly across sessions. When, in Experiment 1, however, the schedule was changed back to the baseline interval schedule (which involved an immediate decrease in rate of reinforcement) there were substantial changes in the temporal structure of responding within a session. Under these circumstances, the structure of responding suddenly shifted to that appropriate to the baseline interval schedule. The duration of such shifts grew longer across sessions until the structure of responding remained similar to that seen under the previous interval baseline.

Although Experiments 1 and 2 were concerned with positive reinforcement, the conceptual analysis of the space included a discussion of negative reinforcement. In the portion of the space where s-->0, schedules of event postponement are arranged when RTE>0. The important aspect of these particular avoidance schedules is that they can be conveniently compared to schedules of positive reinforcement that arrange correlations between responding and events that are equal in absolute value (but opposite in sign) to those arranged by the avoidance schedules. That is, it is possible to arrange schedules of positive and negative reinforcement that are identical, except in terms of the direction of the correlation between responding and events. Such schedules, it was argued, should prove invaluable in comparing the effects of positive versus negative reinforcement, especially in terms of the impact of pharmacological variables.

The problem of the discontinuity of response rate was discussed in relation to a mathematical treatment of schedule-controlled behavior in terms of continuous differential equations. It was argued that response rate may be conceptualized as a measure of the probability of response, a continuous variable. It was pointed out that, ultimately, notions of probability might be dispensed with in a mathematical treatment. Such a treatment would seem to involve describing the spatial locus of the organism or its parts through time. Finally, it was pointed out that

discrete mathematical systems, i.e., difference equations, may be more relevant to schedule-controlled behavior than differential equations.

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